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Geology and Hydrogeology of the STDF Reference Site

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by

R.W.D. Killey and M.H. Klukas

ABSTRACT

One waste management concept currently being considered for the CRL site is a shallow land burial operation titled, a Sand Trench Disposal Facility, or STDF. To formally evaluate the benefits and limitations of such a facility, Waste Management and Decommissioning Operations have sponsored a comprehensive design and assessment program, and the approach chosen has included the selection of a reasonable candidate or reference site at CRL, whose properties and characteristics have then been used in environmental impact assessments, as well as in conceptual facility designs. This report provides a review of general environmental conditions in and around the reference site, but focuses, in particular, on hydrologic, geologic, and hydrogeologic properties and parameters. One criterion for the STDF is that the wastes should be placed above the water table but below grade, which effectively limits options at Chalk River to topographic highs that are composed of sand. The STDF reference site is located in a dune ridge where unsaturated zone thicknesses currently range from 5 to 10 m. An active, unconfined groundwater flow system underlies the site, which transports water at velocities of between 0.25 and 2.1 $m \cdot d^{-1}$, providing a minimum subsurface residence time of 3.2 years. The paths and dimensions of a plume that would form, should contaminants be released from the STDF, are provided here as are the hydrologic properties of surface waters that would eventually receive any mobile and persistent components of a contaminant release. A summary of the methods used in, and the results provided by, a numerical simulation of a region that includes the STDF reference site is included in this report. A summary of aquifer geochemical conditions is also included, again to provide base information for facility design and impact assessment.

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1. INTRODUCTION

1.1 Background and Purpose

This document provides information on the hydrogeologic setting being considered for the Sand Trench Disposal Facility (STDF) concept assessment project [1]. The STDF Project is intended to provide an initial evaluation of the feasibility of establishing and licensing a shallow land burial facility that would be suitable for selected streams of radioactive wastes that are managed by AECL. This document summarizes information on the environment of the reference location for the STDF, with most attention given to the geology and hydrogeology of the region surrounding and downgradient of the site, and hydrologic information for surface water pathways involved in the transport of groundwaters that pass beneath the proposed location. The information provided here will supply input data for several other STDF "Work Packages", including facility design, scoping performance assessment calculations (groundwater/atmospheric, non-radiological contaminants), and environmental monitoring. It should be noted that, apart from the STDF itself, no significant changes in land use or environmental properties are foreseen for the area. Current hydrogeologic conditions, therefore, should also represent conditions in the future.

1.2 Scope

Information presented in this report has been collected as part of a variety of earlier studies in the region of interest - there have been no new data collection or analysis programs undertaken for the current study. For the most part, however, the existing database is sufficient to supply the information needed for this conceptual assessment. One key source that will be used extensively here is the hydrogeologic assessment of the potential for the central portion of the Chalk River Laboratories (CRL) site for shallow land burial facilities that was undertaken in 1988/89 [2]. Primary features sought in that program were unsaturated zone thicknesses greater than 5 m over areas with dimensions of at least 50 x 150 m. Sites with longer groundwater flowpaths before points of discharge to surface waters were also given higher rankings. The location considered here was identified, at that time, as one of the more promising sites under the constraints of that program.

Relevant information is also available from the Preliminary Safety Assessment Report (PSAR) prepared for the Intrusion Resistant Underground Structure (IRUS) site, which is located in an adjacent portion of the same aquifer [3]. A third source of information pertinent to the present study, is an experimental site used in the 1980's to study controls on the dispersion of contaminants in the local sand aquifer. This site is located along the predicted flowpath for the STDF.

The groundwater flow modelling presented in this report is abstracted from a larger scale simulation of flow in the region surrounding Lake 233 and Twin Lake [31]. The simulations were modified to provide data on groundwater flow directions and velocities downgradient of the STDF, but the underlying conceptualization of the aquifer was not altered from that used in the larger scale study.

2. LOCATION OF THE REFERENCE STDF SITE

The STDF reference site is located in the outer area of the 37 km^2 property occupied by AECL's Chalk River Laboratories. The reference site is centrally located within the CRL lands, to which access is controlled - the nearest residence is approximately 3.2 km from the STDF site, and separated by a major water flow divide - the Maskinonge Lake - Chalk Lake channel. The STDF site lies in the Maskinonge Lake drainage basin, approximately 600 m north-northwest of Area C and 250 m north-northwest of the location of the former Nitrate Decomposition Pilot Plant or Nitrate Plant (Figure 1). The reference location is in the dune ridge that forms the southwestern boundary of Lake 233; this ridge has become the host for the two existing waste management facilities noted above primarily because of the appreciable thickness of unsaturated soil in this well-drained topographic high. The target region was identified in the survey conducted in 1988-89 by Inch et al.[2] as an area that might be suitable for additional shallow land burial facilities. Figure 2 displays the study area at a larger scale, and includes the locations of existing boreholes in the region. The footprint for the STDF is positioned to place it over the portion of the underlying unconfined sand aquifer that drains to Upper Bass Lake (with some possible connection to Lower Bass Lake) - details of the placement of the STDF will be discussed in Section 5.2. A large-scale (1:6000) map of surface features (topography, wooded areas, cultural features) is available as CRL Drawing Number E-4500-24.

3. SITE CHARACTERISTICS

3.1 Climate

CRL precipitation data have been collected at the entrance to the Inner Area (approximately 4 km from the STDF reference site) since 1963. Over the measurement period, the annual average precipitation (rainfall and snowfall water equivalent) has been 831 mm [3], with a range from 563 to 1079 mm. A Type 1 Extreme Value analysis of the data predicted that the maximum annual total precipitation in 100 and 500 year return periods would be 1,145 and 1,270 mm, respectively. Over the 33 years of record, the maximum observed daily total precipitation has been 75 mm. The Atmospheric Environment Service (AES) has recorded rainfall intensities at their meteorological station at Petawawa National Forestry Institute (PNFI) between 1961 and 1990 (Station Number 6106400). A Gumbel method of moments analysis of the data from this station provides the rainfall rates listed in Table 1.

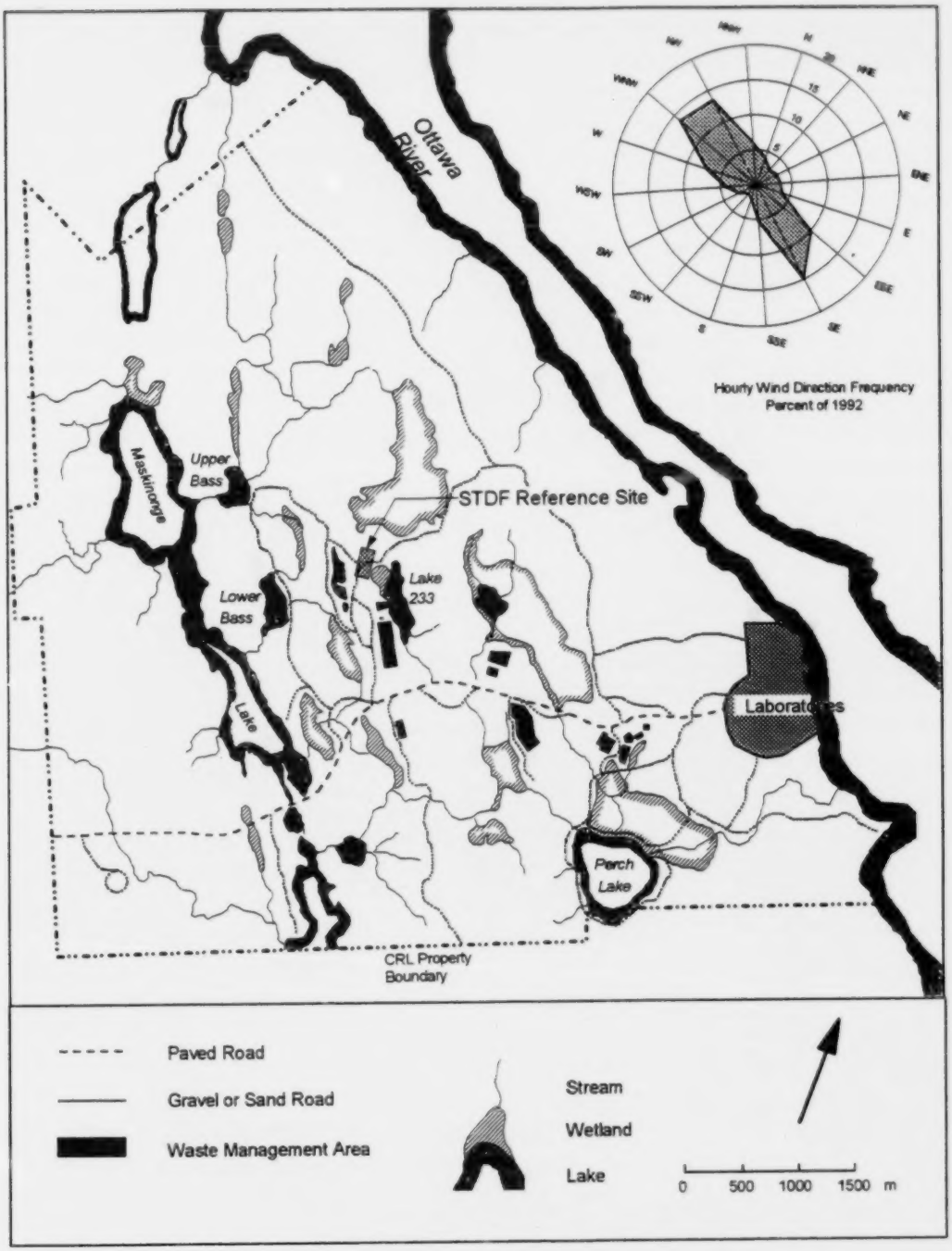

Figure 1. Map of the CRL site showing the location of the STDF, existing waste management facilities, and major surface water features.

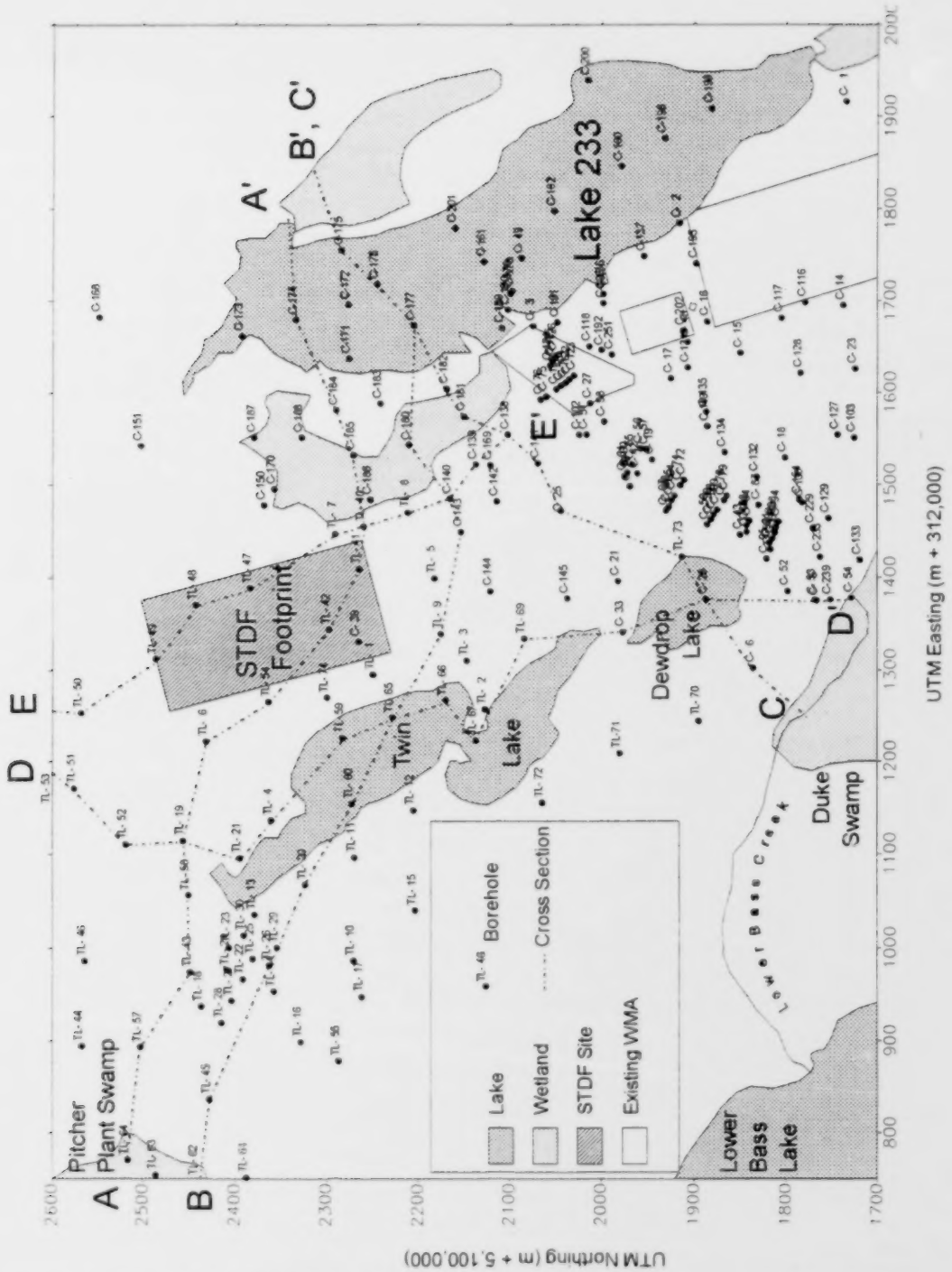

Figure 2. Map of the STDF study area, showing the site footprint, surface water features, and the locations of boreholes.

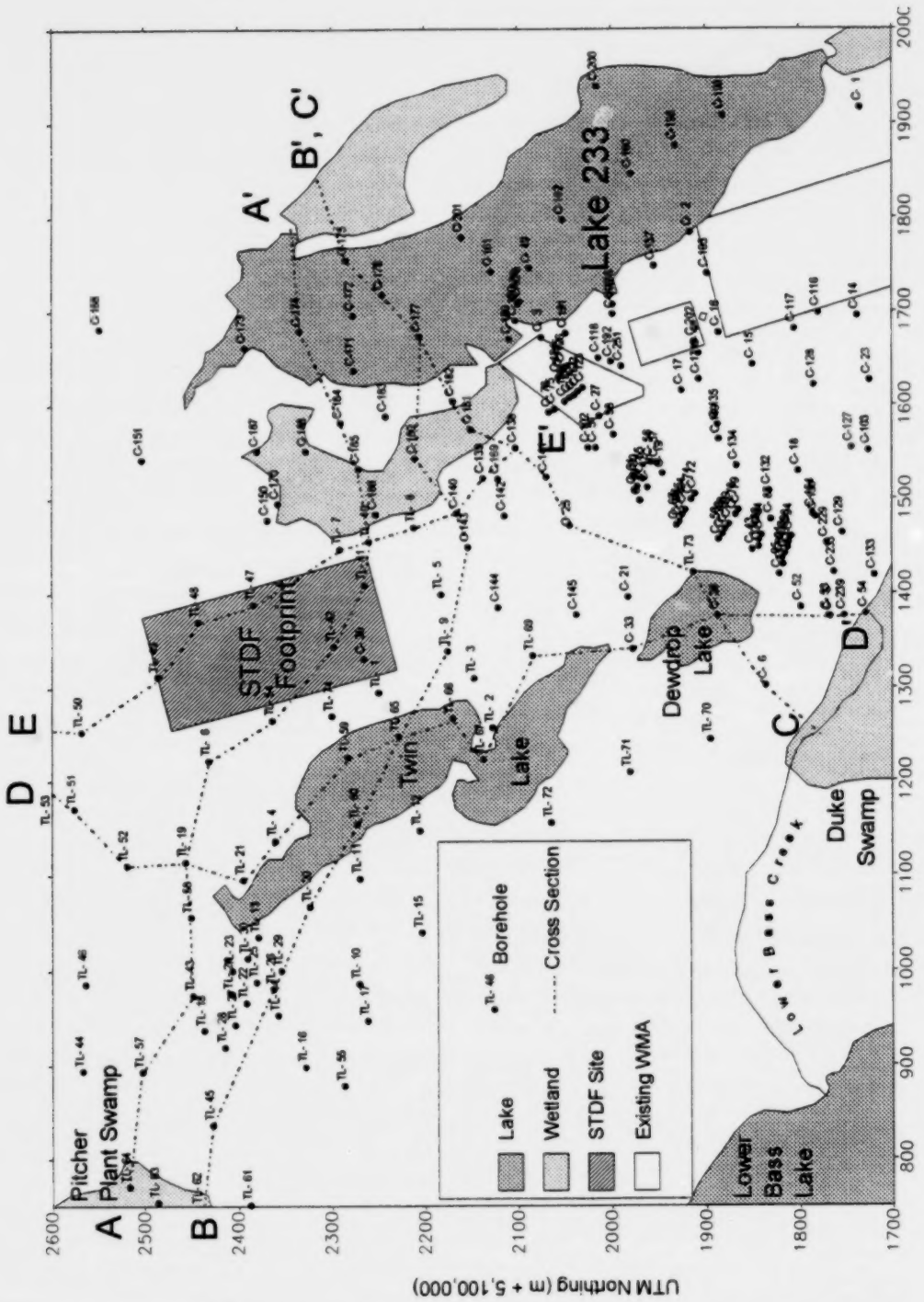

Figure 2. Map of the STDF study area, showing the site footprint, surface water features, and the locations of boreholes.

Table 1. Rainfall Intensity Predictions

Rainfall Duration	Rainfall Intensity (mm/hr) ± 95% Confidence Limits					
	2 Yr Return Period	5 Yr Return Period	10 Yr Return Period	25 Yr Return Period	50 Yr Return Period	100 Yr Return Period
5 min	93.8 ± 14.6	132.3 ± 24.5	157.9 ± 33.2	190.1 ± 44.7	214.0 ± 53.6	237.8 ± 62.3
10 min	63.0 ± 9.2	87.2 ± 15.4	103.2 ± 20.8	123.5 ± 28.1	138.5 ± 33.6	153.4 ± 39.1
15 min	51.8 ± 7.4	71.7 ± 12.5	85.0 ± 16.9	101.7 ± 22.8	114.1 ± 27.3	126.4 ± 31.8
30 min	31.8 ± 4.3	43.4 ± 7.3	51.1 ± 9.8	60.8 ± 13.2	68.0 ± 15.8	75.2 ± 18.5
1 hr	19.3 ± 2.7	26.5 ± 4.5	31.3 ± 6.1	37.3 ± 8.2	41.8 ± 9.8	46.2 ± 11.5
2 hr	12.0 ± 1.9	17.0 ± 3.1	20.3 ± 4.2	24.5 ± 5.7	27.6 ± 6.8	30.7 ± 7.9
6 hr	5.1 ± 0.8	7.3 ± 1.4	8.7 ± 1.8	10.5 ± 2.5	11.8 ± 2.9	13.2 ± 3.4
12 hr	3.2 ± 0.4	4.4 ± 0.8	5.2 ± 1.0	6.2 ± 1.4	6.9 ± 1.6	7.7 ± 1.9
24 hr	1.8 ± 0.2	2.5 ± 0.4	2.9 ± 0.5	3.4 ± 0.7	3.8 ± 0.9	4.2 ± 1

Not all precipitation is available for infiltration or runoff. Local rates of evaporation and evapotranspiration have been derived from studies conducted in the Perch Lake Basin from 1969 to 1980 during the International Hydrologic Decade. Robertson and Barry [4] reported on studies of lake evaporation and terrestrial evapotranspiration in the Perch Lake basin over that period. Table 2 summarizes their results and compares them to regional data derived from the Hydrological Atlas of Canada [5].

Table 2. Precipitation, Evaporation, Evapotranspiration, and Recharge/Runoff Data

Component	Perch Lake (mm)	Hydrological Atlas* (mm)	STDF (mm)
Precipitation	773	800 and 900 (Plates 3 and 25)	831
Lake Evaporation	690	620 (Plate 17)	690
Evapotranspiration	490	510 (Plate 25)	530
Recharge/Runoff	280	290 (Plates 3 and 25)	300

* Fisheries and Environment Canada (1978)

Although measurements for the period of the Perch Lake study provided an annual average precipitation of 773 mm, the longer-term annual mean of 831 mm has been used for the STDF evaluation. Because of the higher precipitation input, an annual evapotranspiration flux of 530 mm has been recommended for the STDF case, based on an assumption that the higher annual precipitation for the 1963 to 1990 period comes slightly closer to satisfying the soil moisture deficit that limits evapotranspiration in summer. Lake evaporation, however, should be unaffected by small variations in annual precipitation, so the figure of 690 mm·a^{-1} has been employed for hydrologic components of the current study.

The annual evapotranspiration flux of 530 mm applies to fully vegetated surfaces. During the operating phase of the STDF, portions of the site will be covered with unvegetated soils, and the transpiration component of water loss to the atmosphere from surface will not be present. Chow et al. [6] have noted that in agricultural water balance studies, the rate of water loss from an unvegetated surface (or a surface during periods of the year when plants are inactive), is 35% of the rate observed for the same surface when plants are present and active, and when water is not a limiting factor for plant activity. At CRL, however, water is a limiting factor for plants in much of the season of active growth between early May and late September. During most of this period, the potential demand for water exceeds the available supply from precipitation [7]. During a four-year period, Shiau [7] estimated that the potential annual evapotranspiration from the Perch Lake basin averaged 628 mm, and it is this figure, rather than the actual evapotranspiration, that should be used to estimate the rate of water loss from unvegetated surfaces. That is, evaporation rates from unvegetated surfaces at Chalk River should be 220 mm per year, leaving 610 mm available for infiltration or runoff. Partially vegetated surface will result in intermediate rates of water loss to the atmosphere.

Temperature records have also been maintained at the CRL site - monthly mean temperatures for the 1963 - 1993 period are shown in Figure 3. During the months of December to March, almost all operations at the site will be carried out under freezing conditions. Frost penetration into the soil imposes some constraints on design and operation - measurements made over five years in an area of undisturbed snow cover by Wildsmith [8] found frost penetration limited to about a 10 cm depth. Observational evidence, and the National Building Code for Canada [9], however, indicate that in areas kept clear of snow, frost can penetrate to depths in excess of a metre. The code recommends that a frost penetration depth of 1.85 m be assumed for the CRL site.

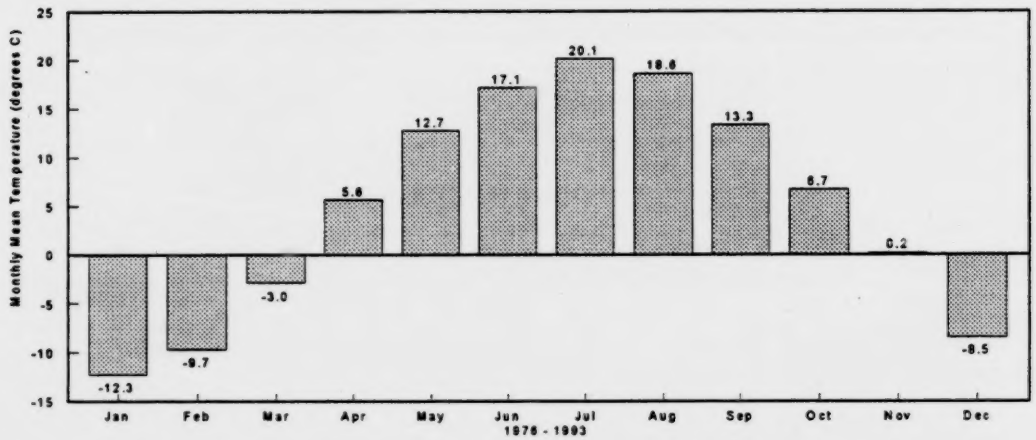

Figure 3. Mean monthly temperatures at CRL between 1963 and 1990.

3.2 Surface Conditions

Lake 233 is better considered as a seasonal wetland than a lake, although in years when water tables are relatively high, a substantial portion of the lake's basin does contain some water through the summer. Water depths rarely exceed 1 m, however, and in periods when water tables are relatively low, much of the lake is a sedge-filled, wet meadow in mid to late summer. The bedrock-controlled ridge to the northeast of Lake 233 is covered with a mixed coniferous-deciduous forest, whereas the wind-deposited sands to the southwest, where the STDF footprint is located, are dominated by coniferous trees (jack, red, and white pine in order of abundance) and poplar. The region was burnt over in the 1920's or early thirties [10] by a major fire, with burnt stumps or "chicots" still widespread through the study area. The crests of the dune ridges tend to have a parkland character, with fairly widely-spaced trees and little development of second-storey growth. Ground cover in these regions is dominated by bracken, grasses, and, mosses and lichens. In open areas, patches of low-bush blueberries are fairly common. Wetland areas that receive groundwater discharge, and that are saturated at essentially all times, frequently have a perimeter stand of eastern cedar, with white spruce and red maple in more central portions of the wetlands. Wetland surface cover is dominated by mosses and sedges, and Pitcher Plant Swamp contains scattered clusters of its namesake plant.

There is no evidence (in the form of clearings visible in early air photos of the site, remnant foundations of buildings, old fencelines, rectilinear plantations) that the region surrounding the STDF site has been used for agricultural purposes. The very rapid drainage and poor nutrient retention characteristics of the surficial sands have made soils in the study area considerably less attractive agricultural soils than the loamier tills and silty sands that are found on and around the CRL site. Soils in the region between Lake 233 and Twin Lake, are members of the Uplands fine sand soil group, which has agricultural ratings from Classes 4 to 6 (severe agricultural limitations to suitable only for improved pasture, respectively). Sands in the study area, because of the topography and depth to water table, would fall at the low end of the agricultural suitability scale. It appears that people, who formerly farmed portions of the CRL property, judged that the STDF region was unsuitable for cultivation or pasture.

A fire approximately 60 years ago is still the most evident feature in the current forest in the study area. It is very probable, however, that the region has been logged in the past. In their 1988 survey, Dendron [10] rated the mixed poplar-pine forest of the region as "Fair Site Class", with a poor current cover but suitable for improvement by forest management. Most of the poplar are infected with fungi, there are few high-quality pine logs, and growth rates are low. The lower-lying areas around Lake 233, Twin Lake, and the groundwater discharge areas, are rated "Poor Site Class" by Dendron [10], with poor current cover and not supportive of efforts to improve the value of the forest by managed intervention.

The dune ridge that is the proposed host of the STDF, and a second dune ridge that lies near the Pitcher Plant Swamp, are the dominant topographic features in the study area. Both of these ridges stand 15 to 20 m above the surrounding landscape, are particularly prominent because of their frequently steep side slopes. These slopes locally approach the angle of repose for sand at angles to the horizontal of 30° - in civil engineering terminology this would be termed a 60% slope. Shallow, closed dry depressions are also a feature of the topography in the region between Lake 233 and the Duke Swamp - Pitcher Plant Swamp groundwater discharge area. At a

somewhat larger scale, the study area is located on the southwest side of the CRL "island", the bedrock-controlled topographic high that separates the Maskinonge Lake and Ottawa River drainage basins. The stratigraphic sections presented in the following section provide a set of vertical transects that display topography in profile, albeit at an exaggerated vertical scale.

The STDF footprint is located 1.4 km north of the paved Plant Highway, with current access to the STDF site by gravel and sand roads. Some of these unpaved roads may have originated as logging trails, but they currently serve as routes to waste management facilities and sand borrow pits in the region, for fire control and for access to experimental facilities and site monitoring equipment and stations. The road to Area C is approximately 7.5 m wide, graveled, and suitable for trucks in all weather. The remaining sideroad to the STDF site (700 m) is presently about 5 m wide and is not suitable for all-weather truck access. The STDF footprint currently straddles the intersection between two sand roads - one that circles Twin and Dewdrop Lakes, and one that links the Lake 233 - Twin Lake region with the Old Mattawa Road, a gravel road that follows the drainage divide for direct runoff to the Ottawa River from CRL to the Balmer Bay site boundary. Although these road links should be maintained, they could be interrupted for substantial periods of time without causing a major impediment to other users of the CRL Outer Area.

4. GEOLOGY

4.1 Surficial Geology

Surficial geology of the region was mapped by Gadd during the period between 1958 and 1962 - results of that work were presented in a map with notes [11]. Catto et al. [12] provided an added discussion of the processes involved in the post-glacial development of the region from des Joachims to Pembroke, and more recently AECL [13] undertook a review and update of surficial geology and overburden stratigraphy on the CRL site for the Siting Task Force. Bedrock, or a thin layer of bouldery till over bedrock, forms the surface cover to the east-northeast of Lake 233. There is a small, but significant, bedrock outcrop on the western shore of the southern basin of Twin Lake. Sands make up the surface material between Lake 233 and the Duke and Pitcher Plant Swamps; thin sand and till mantle the surface in the region between Duke and Pitcher Plant Swamps and extend down the hill to Lower Bass and Upper Bass Lakes. Organic soils cover the surface in wetlands. Organic sediments are generally thin in the bed of Lake 233. Here accumulation is limited by the frequent drying of much of the lake's area in summer and fall - a known exception is a small pocket around borehole C-175 (Figure 5) where more than 2 m of peat was encountered. Duke Swamp, which does not undergo seasonal drying, contains up to 3 m of peat. Organic soil thicknesses in Pitcher Plant Swamp are not well known; although 3.8 m of peat and sand were encountered in borehole TL-64.

4.2 Stratigraphy

4.2.1 Introduction

Figure 4 to Figure 8 are a set of 5 cross sections that display vertical transects through the study area along the lines A-A' to E-E' shown on Figure 2. For much of the subsequent discussion, we will focus on Sections A-A' and D-D', which are approximately oriented perpendicular and parallel to the topographic fabric of the area, respectively. Attention will also be directed towards unconsolidated sediments, which are the primary media for groundwater flow in the area, but the sequence begins with bedrock.

4.2.2 Bedrock

Bedrock on the CRL site consists of crystalline Precambrian metamorphics, most of which are of a granitic composition, although their generally lower silica content places most of the rock in the category of monzonites. These rocks are very old; the last major event of heating and compression was 1150 - 1100 million years ago. The rock is also moderately fractured, and features a number of sets of faults that have had a large influence on the topography of the bedrock surface, since faults are regions of preferential erosion. The most readily evident, and apparently the largest, faults in this section of the Ottawa Valley are the ones that define the Ottawa-Bonnechere Graben, a rift valley that was last involved in substantial movement between 500 and 440 million years ago [14]. The Quebec shore of the Ottawa River is one of the major bounding faults of the graben, with the other boundary located approximately 50 km to the southwest (along which sections of the Bonnechere River now flow). There are, however, a number of smaller faults within the graben, with one prominent set oriented parallel to the boundary fault and two sets at approximately 60° to the valley axis.

Large scale topography in the CRL area is controlled by enhanced erosion by ice and water along the rift valley boundary fault that defines the Ottawa River valley and by sub-parallel subsidiary faults, such as the one defined by the Maskinonge Lake - Chalk Lake channel. The cross-cutting character of the sets of faults, however, has also resulted in bedrock erosion into a smaller scale knob and kettle (closed depression) topography with elevation differences of a few to a few tens of metres and lateral scales that are one to two orders of magnitude greater. Figure 9, displaying bedrock topography in the immediate vicinity of the STDF footprint, is based on surface topography where bedrock comes to surface, and on borehole and geophysical data where unconsolidated sediments overly the rock.

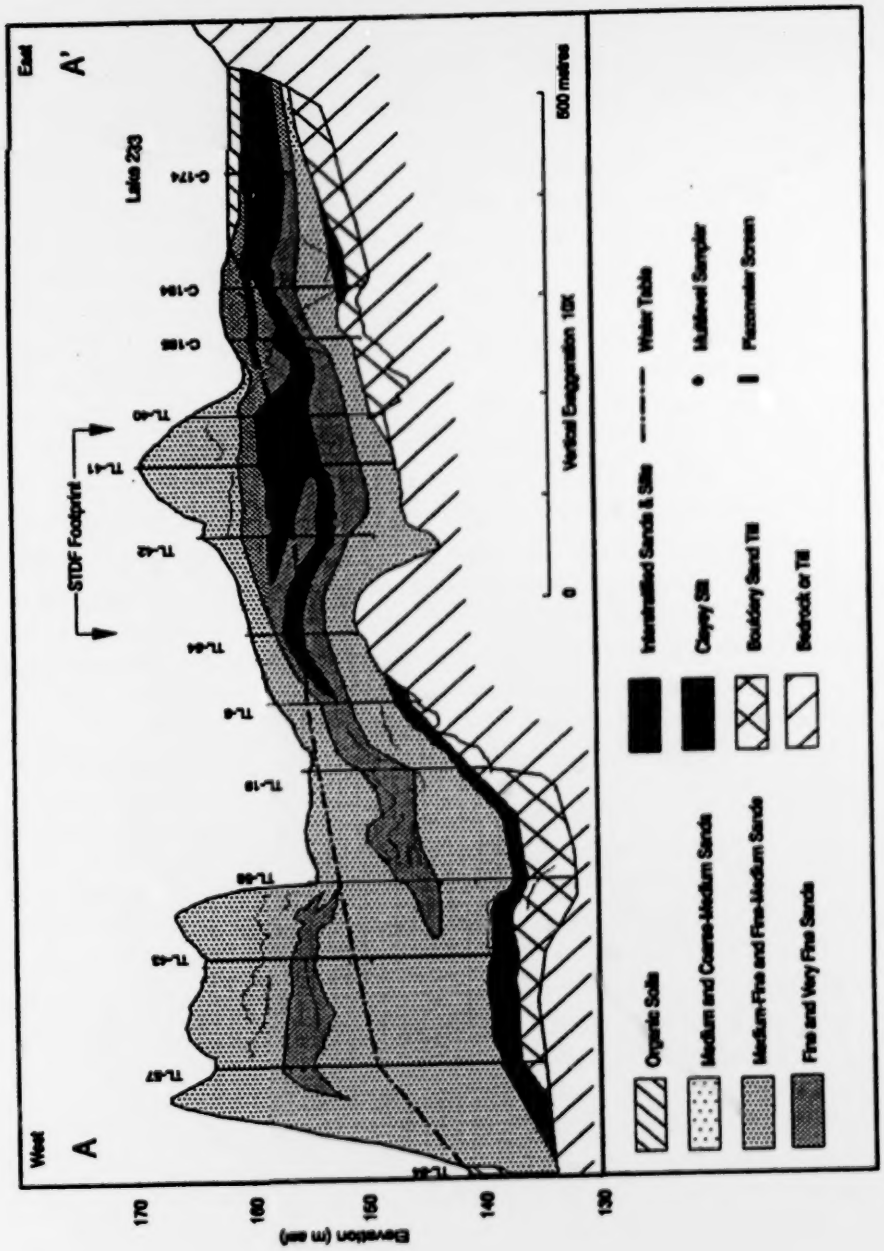

Figure 4. Stratigraphy along cross section A-A', from Pitcher Plant Swamp through the STDF footprint to Lake 233.

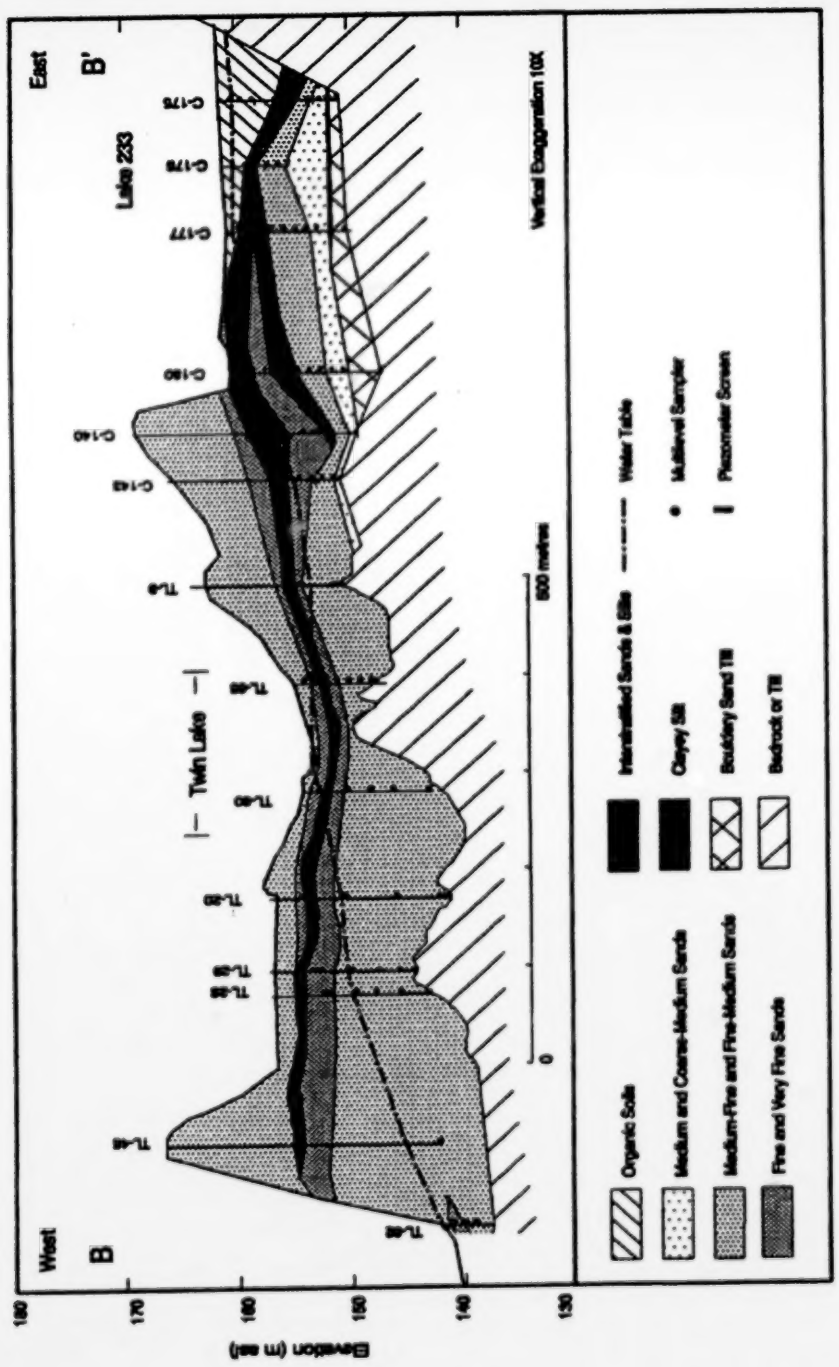

Figure 5. Stratigraphy along cross section B-B', from Pitcher Plant Swamp through Twin Lake to Lake 233.

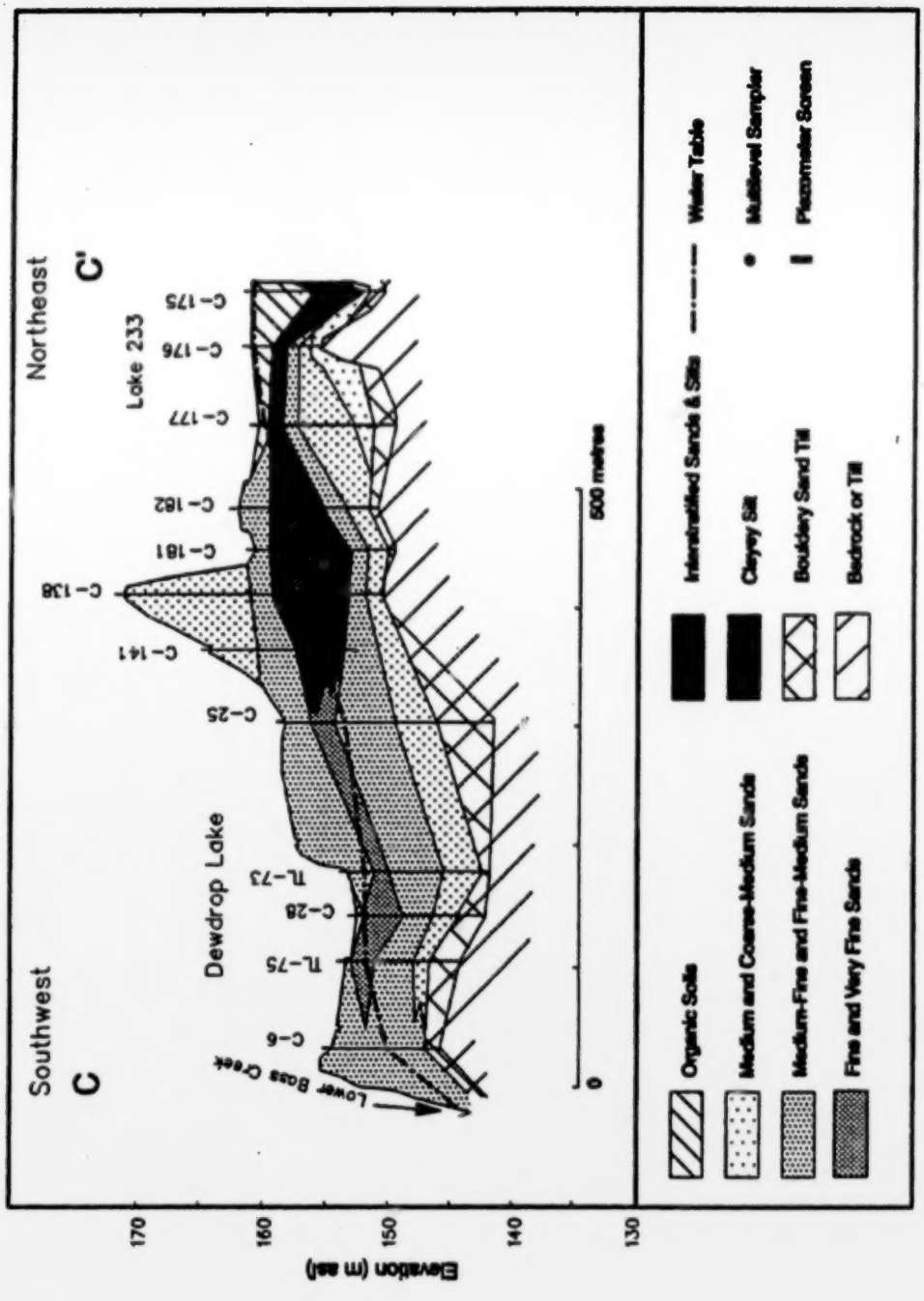

Figure 6. Stratigraphy along cross section C-C', from Duke Swamp to Lake 233, passing south of the STDF location.

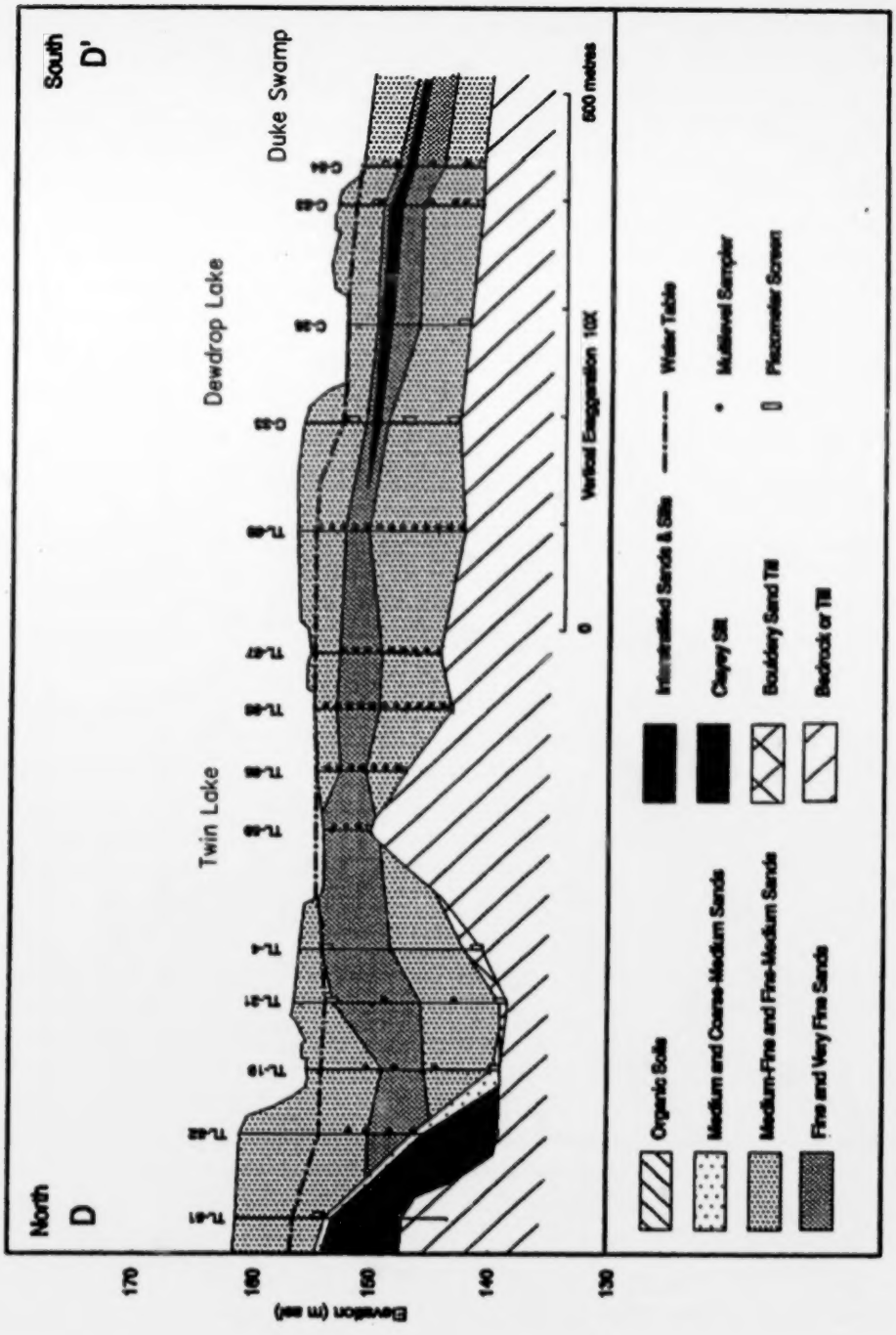

Figure 7. Stratigraphy along cross section D-D', from north of Twin Lake to Duke Swamp west of the STDF location.

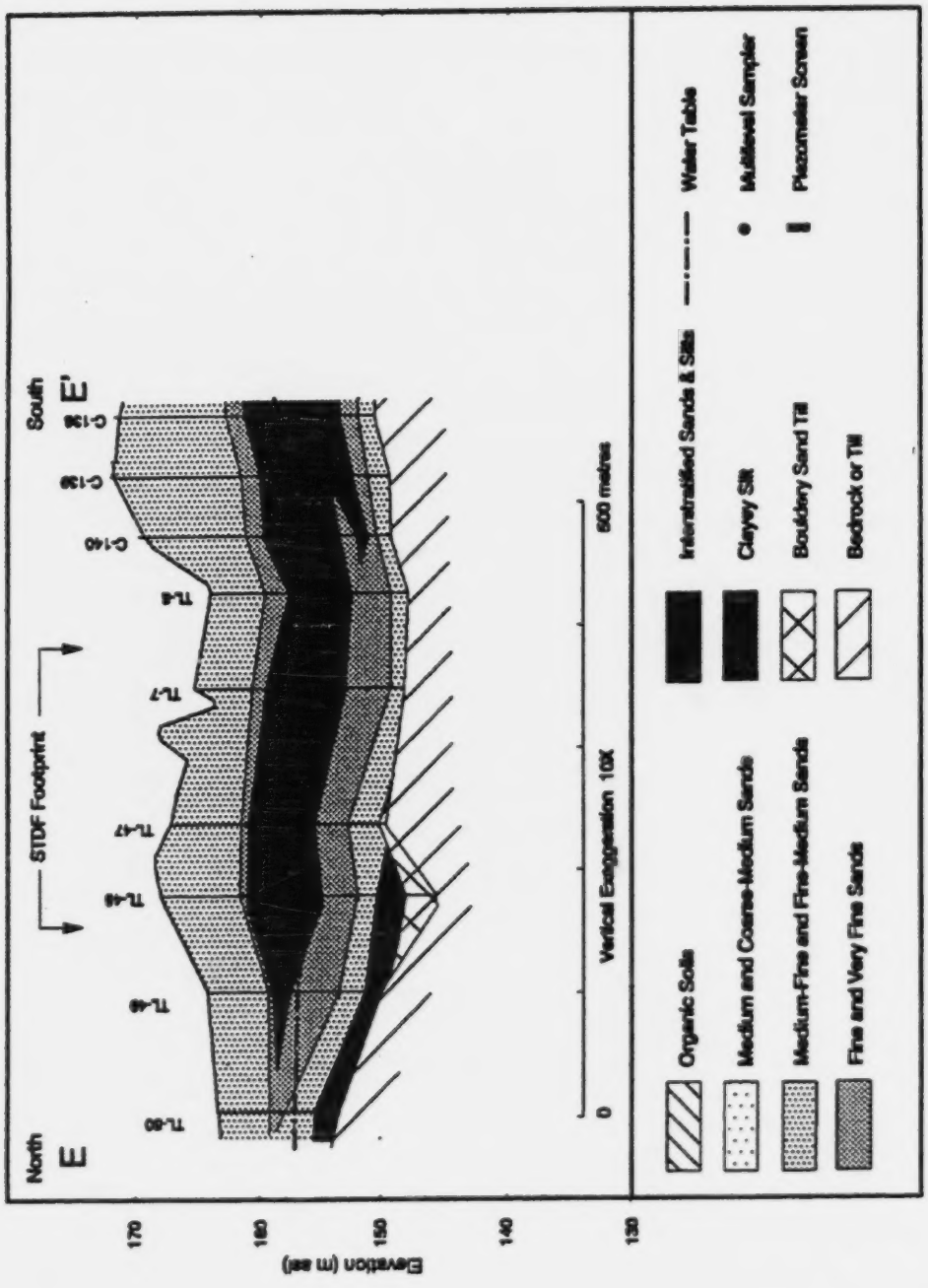

Figure 8. Stratigraphy along cross section E-E', from north to south along the eastern margin of the STDF location.

The knob and kettle character of the bedrock surface is very evident on this contour plot, and on the stratigraphic sections, which show that rock topography is a major control on sediment thickness and, more importantly, on aquifer thickness. Bedrock highs form outcrops to the northeast of Lake 233, to the southwest of Duke Swamp, and along a portion of the southern shoe of Twin Lake, where the bedrock elevation is greater than 152.5 m (Figure 9). In the map area, the largest bedrock depression (800 by 300 m) is centered near Dewdrop Lake and trends north-northwest, towards the bedrock valley that extends northwest from the northern section of Twin Lake. A key feature of the bedrock topography for the STDF program is the bedrock ridge that separates the Dewdrop depression from this bedrock valley. This ridge extends from the area of bedrock outcrop on the southwest shore of Twin Lake to the north-northeast, crossing beneath the central section of Twin Lake's northern basin. The ridge is evident on cross sections A-A', B-B', and D-D' near boreholes TL-54, 65, and 59, respectively, where it decreases aquifer thickness from greater than 6 m to 3 m or less.

4.2.3 Unconsolidated Sediments

All of the unconsolidated sediments in the study area date from late in the last glaciation to modern. Glacial till is defined as sediment that has been deposited directly from ice. Characteristic features of such sediments are a wide range of grain sizes in deposits that frequently show no readily discernible layered structure. At CRL, much of the glacial till is composed of materials ranging from silts to boulders, some the size of a truck. Till deposits on CRL (and surrounding) property are frequently thin and patchy in their areal extent - in the region of the STDF glacial till is found only in portions of bedrock depressions. Small units of till are shown on all of the stratigraphic sections, with till thicknesses displayed as being no more than 5 m. The presence of large boulders in the till make diamond drilling necessary if one wants absolute assurance that auger drilling (the most commonly used technique in the STDF area) has stopped on bedrock rather than a boulder. That is, the position of the till-bedrock contact may differ slightly from that shown here.

Fluvial, or river-deposited, sediments make up the next unit in the overburden sequence. Medium and fine sands dominate the fluvial sediments, which were deposited by the Ottawa River between 10,000 and 9,000 years before present (BP) when large volumes of meltwater from what is now Lake Superior and from Lake Agassiz (which occupied southeastern Manitoba) drained through the Ottawa Valley. The sands feature well-defined laminations and larger bedding structures and are generally well-sorted (i.e. with a small range of particle sizes) The fluvial sediments, however, also include limited deposits of clayey silts, and a widespread unit of interstratified sands and silts. Contacts between the sands and the interstratified sand and silt units are frequently gradational and indistinct. The clayey silt units frequently have well-defined contacts, although they may be contained in silt to sand transitional unit.

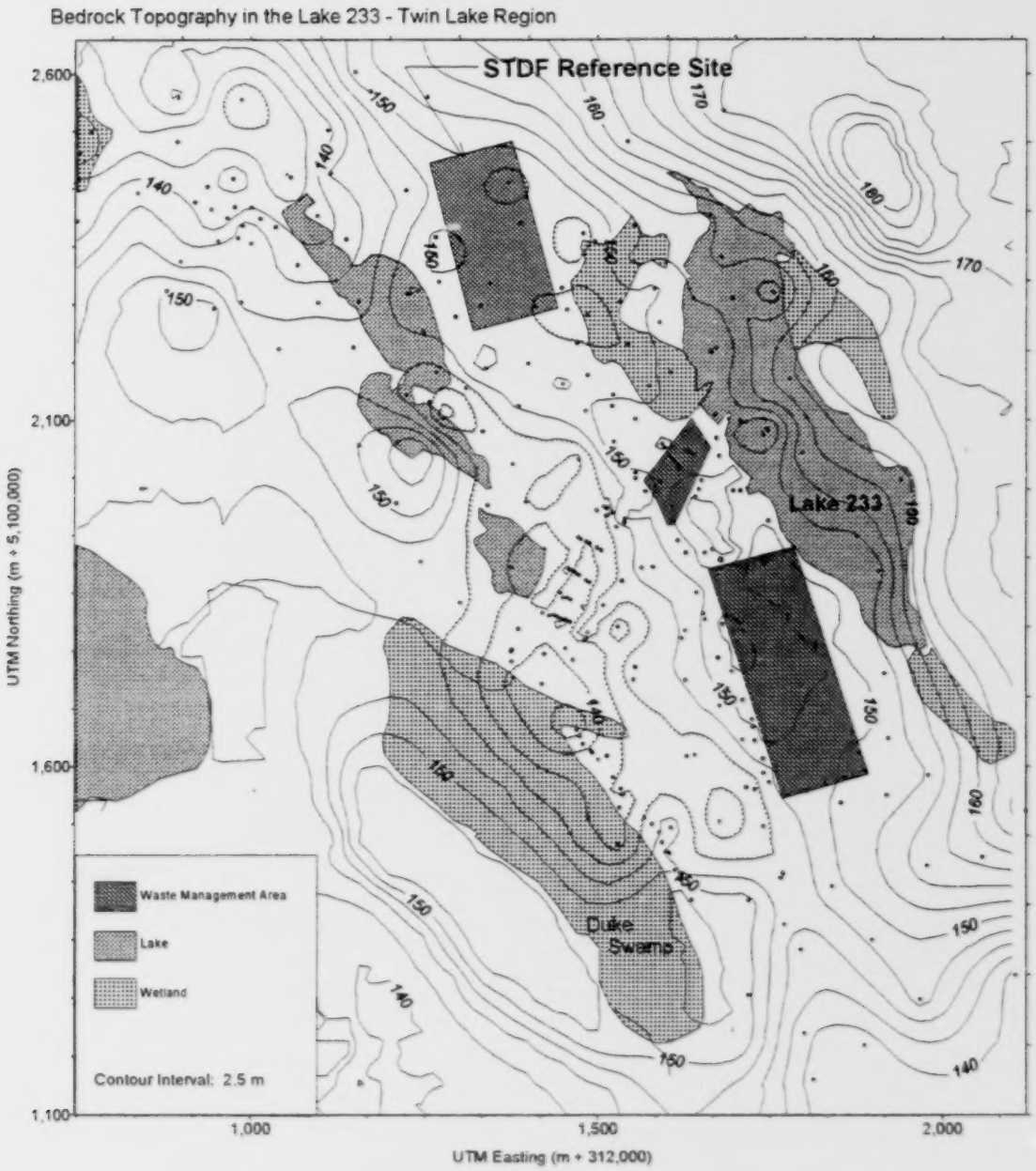

Figure 9. Bedrock topography in the vicinity of the STDF based on rock exposures, borehole data, and ground penetrating radar surveys.

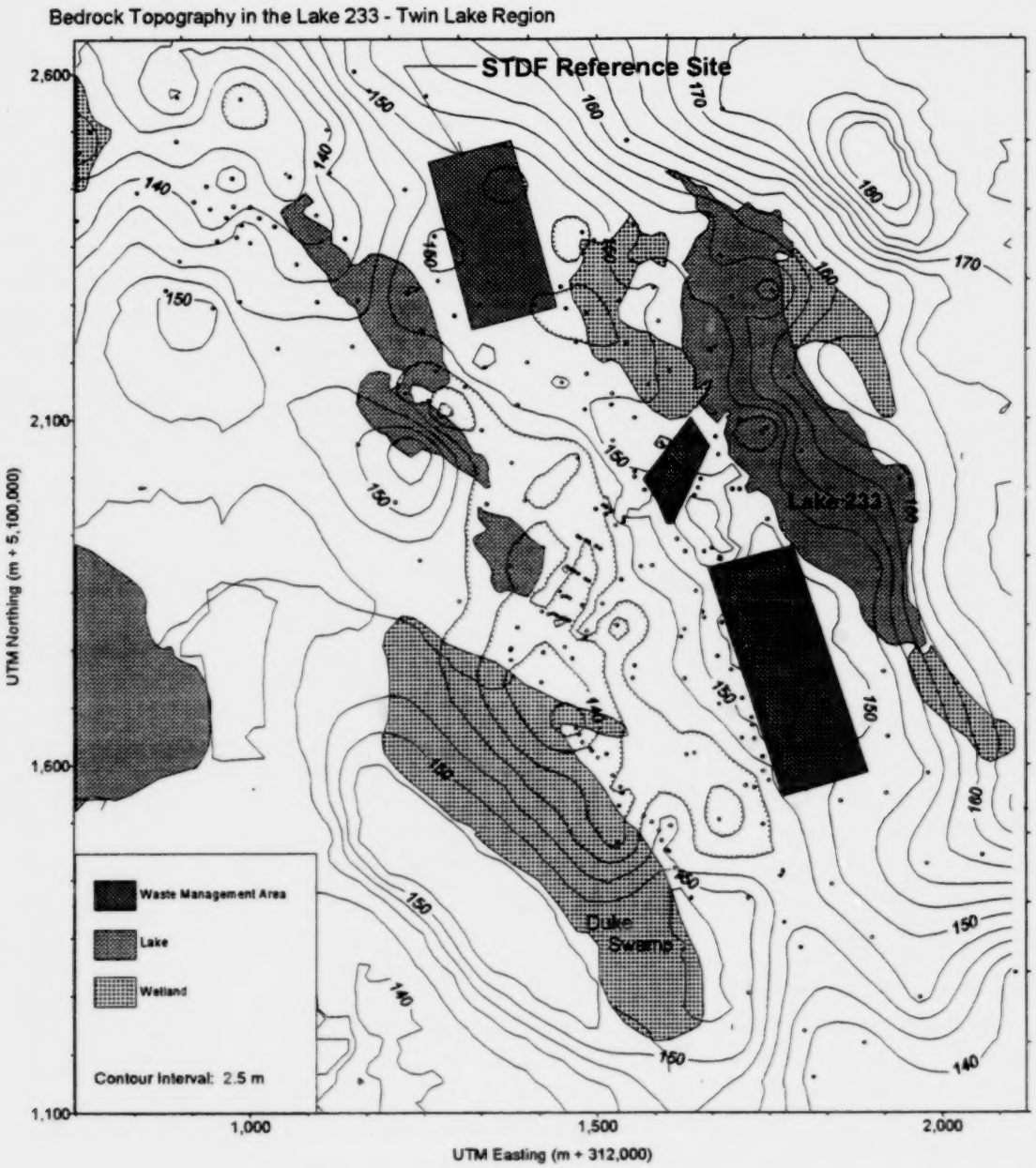

Figure 9. Bedrock topography in the vicinity of the STDF based on rock exposures, borehole data, and ground penetrating radar surveys.

All evidence indicates that there was an abrupt decrease in the volume of flow through the Ottawa River between 9,000 and 8,900 years BP, and the decrease in river level left large areas of unvegetated sand exposed. Wind speeds at that time appear to have been considerably higher than they are at present (although prevailing wind directions appear to have been similar to those that are currently observed) and some of the exposed sands were re-mobilized by wind. There are widespread sheet deposits of sand on the CRL property, but the most prominent aeolian features are the dunes that have been constructed. The dunes are particularly prominent in the vicinity of the STDF reference site - the ridge that contains the STDF footprint is a dune, and a second dune ridge forms the topographic high to the west of Twin Lake. The ridges trend north-northwesterly, parallel to the prevailing winds, and are most evident in cross-sections that transect them (Figure 4, Figure 5 and Figure 6).

Fine to medium sands dominate the aeolian deposits, although there are local small units of slightly silty very fine sand contained within the dune and sheet deposits. Geologic and geomorphic evidence leads to a conclusion that the period of aeolian sediment transport was short, and that there has been no significant movement of these sands for at least the last 8,000 years. Detailed discussions of the genesis and depositional history of the CRL site are provided in a report prepared for the Siting Task Force [13] and in the preliminary safety assessment for the nearby IRUS facility [3]. Continued concerns about dune stability at the IRUS site led to the preparation of an unpublished, but available, report by Brookfield (1996) which concluded that the dunes have been essentially immobile since their initial formation, and that with vegetated surfaces and the current wind regime, the dune will continue to be stable.

The last (most recent) sedimentary materials in the study area are organic soils that have accumulated in wetlands throughout the region. Apart from a small pocket in the northeastern corner of Lake 233 (at borehole C-175), where the bottom of the 3 m of accumulated peat was carbon dated at 8,900 years before present, most of the significant accumulations of organic debris in the study area are in the wetlands supplied by groundwater discharge - Duke and Pitcher Plant Swamps. There are, at present, no dates for the start of organic soil accumulation in these wetlands, but it seems reasonable to assume that they also began to form around 9,000 years ago.

5. HYDROLOGY AND HYDROGEOLOGY

5.1 Surface Hydrology

The reference STDF site is positioned such that groundwaters that pass beneath the site discharge to Pitcher Plant Swamp, flow overland to Upper Bass Lake (with a possible component to Lower Bass Lake), and then through the Maskinonge Lake - Chalk Lake system to the Ottawa River. Table 3 summarizes information on the surface water systems involved in the flow system downgradient of the STDF site. Robertson [15] provided maps of the areal extent and bathymetry of Maskinonge, Upper Bass, and Lower Bass Lakes; data on the area, volume, and maximum depths of these lakes were provided by a software package (Surfer) after digitizing the maps of the lakes. Flow data for the Ottawa River at des Joachims were provided by Ontario Hydro, while data for Carillon (near the confluence of the Ottawa River and the St. Lawrence River) was taken from the Hydrological Atlas of Canada (1978). Flow data for the other watercourses listed in the table are derived from calculations using the basin areas shown on

Figure 10 and the annual average quantity of precipitation in excess of evapotranspiration losses. The only exception to this is measured flow at Lower Bass Creek, where a weir with a continuous recorder has been in operation since 1987. Table 3 provides the average annual flow measured in Lower Bass Creek, as well as the calculated discharge.

Table 3: Surface Hydrologic Data for the STDF Reference Site

			Ottawa River		Chalk Lake	Maskinonge Lake	Upper Bass Lake	Upper Bass Creek	Lower Bass Lake	Lower Bass Creek
			des Joachims	Carillon						
Basin Area	(m2)		6.35E+10	1.48E+11	2.48E+08	1.94E+07	4.78E+06	1.05E+06	1.20E+06	6.79E+05
Lake Area	(m2)				3.62E+06	1.74E+06	5.60E+04		1.10E+05	
Lake Vol.	(m3)				2.53E+07	1.18E+07	2.50E+05		4.20E+05	
Max Lake Depth	(m)					17.0	9.0		11.0	
Mean Lake Depth	(m)				7 (assumed)	6.8	4.5		3.8	
Annual Input (precip)	(m3)				2.05E+08	1.61E+07	3.95E+06	8.71E+05	9.96E+05	5.62E+05
Ann Evapotrans	(m3)				1.29E+08	9.47E+06	2.50E+06	5.58E+05	5.90E+05	3.60E+05
Ann Lake Evap	(m3)				2.49E+06	1.20E+06	3.85E+04		7.56E+04	
Mean Residence	(years)				0.29	1.81	0.15		1.04	
Calc. Ann Net Flux	(m3)				7.30E+07	5.40E+06	1.41E+06	3.13E+05	3.30E+05	2.02E+05
Meas. Ann Net Flux	(m3)		2.65E+10	6.19E+10						2.04E+05

Mean residence times listed for the lakes are simply the annual input to the lake divided by its volume - uniform mixing at all times is assumed. All of the lakes are well-mixed in spring, when they are isothermal and subject to wind-driven circulation, and in the fall when the reversal of thermal stratification causes lake turnover. Mixing may not be complete during the summer (when the lakes are thermally stratified [15]) and beneath ice cover in the winter, but provided that assessment simulations use time steps of one year or greater, the assumption of complete mixing in the lakes is a reasonable one. Residence times have not been calculated for the streams and wetlands. Residence times in study area streams are on the order of hours to (possibly) a few days. Water residence times in wetlands are appreciably greater - if one assumes an average water depth of 0.2 m in the southern section of Duke Swamp, surface water would take, on average, 2 months to drain from the wetland.

It should be noted here that a recent assessment of wetlands on the CRL property has concluded that a wetland that drains to the northeast corner of Lower Bass Lake is not clearly separated from Pitcher Plant Swamp. Measurements of rates of flow from this wetland will be undertaken to constrain the size of its catchment and determine whether Lower Bass Lake is a significant potential receptor for an STDF plume.

All of the surface water bodies noted here, with the exception of Chalk Lake and the Ottawa River, are contained within the CRL property and are not currently accessible to the public. Chalk Lake straddles the CRL - CFB Petawawa property boundary, and again is not accessible to the public. The Ottawa River is the source of water for all municipalities that border the river, probably supplies some cottage and rural residences, and is a major recreational feature of the Upper Ottawa Valley.

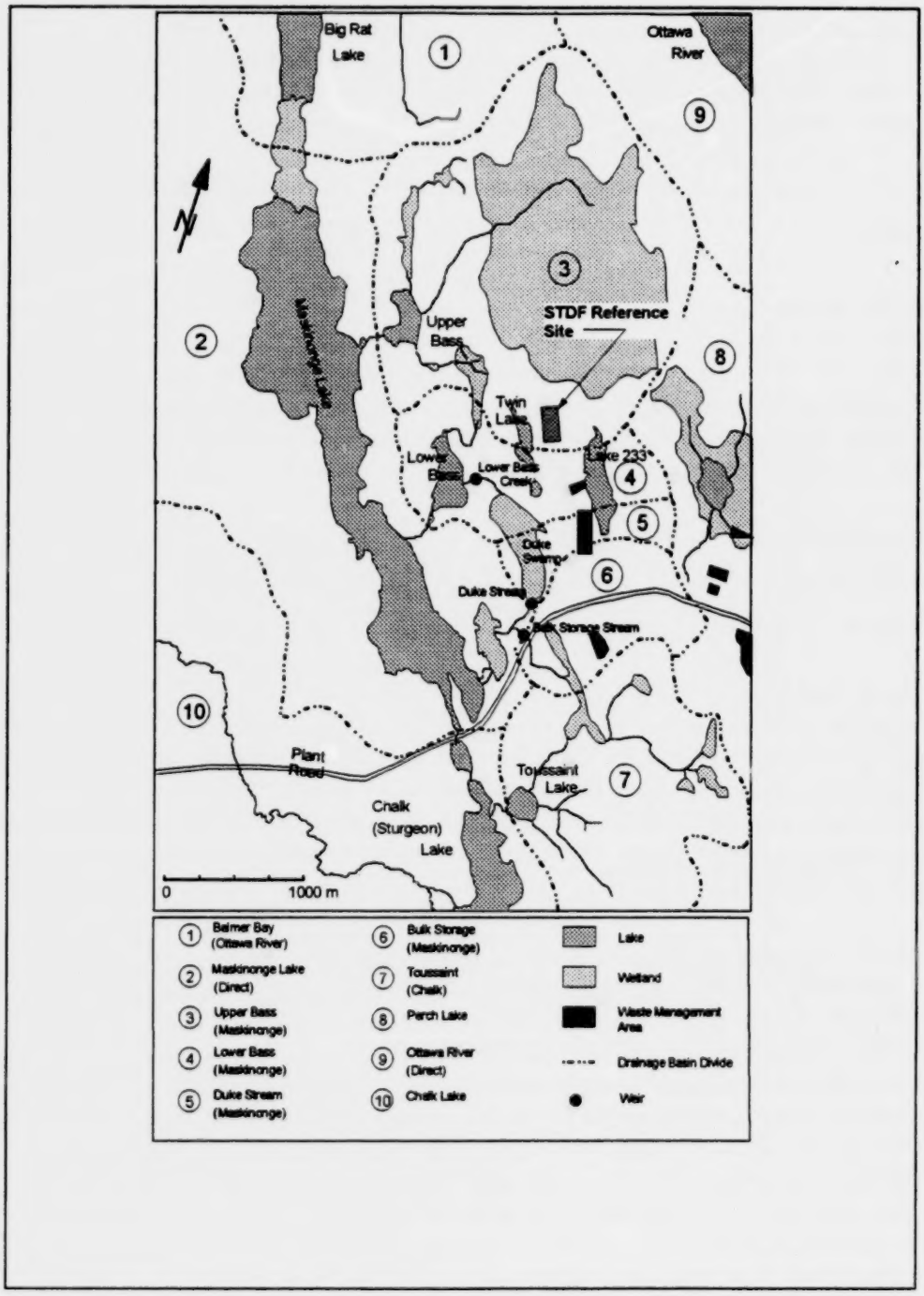

Figure 10. Drainage basins in the eastern portion of the Maskinonge Lake catchment.

A detailed description and discussion of wetland characteristics, flora, and fauna, as well as a limited set of surface water quality parameters, are provided by CH2M Gore and Storrie [16]. A comprehensive set of surface water quality data, however, is not currently available.

5.2 Hydrogeology

5.2.1 Physical Properties

Geologic materials in the study area can be classified into five hydrostratigraphic units - soils or rock with similar hydrogeologic properties. Table 4 summarizes recommended hydraulic conductivities, porosities, and dispersivities for the units, and the following paragraphs provide some explanatory or expansionary comments.

Table 4: Hydraulic Properties of Hydrostratigraphic Units Recommended for Use in Groundwater Transport Calculations at the STDF Reference Site

Hydrostratigraphic Unit	Hydraulic Conductivity ($cm \cdot s^{-1}$)	Porosity	Longitudinal Dispersivity (m)	Transverse Dispersivity (m)
Bedrock	5.8×10^{-5}	0.01		-
Bouldery Sand Till	1.4×10^{-5}	0.32		
Clayey Silt	1.3×10^{-6}	0.45		
Interstrat. Sand & Silt	4.6×10^{-3}	0.40	5	0.5
Fine - Medium Sand	1.9×10^{-2}	0.40	0.34	0.02

Crystalline Bedrock: The most recent, and one of the most broadly based, data sets for hydraulic properties of the upper regions of the bedrock at CRL comes from the drilling and testing performed by the Applied Geoscience Branch (AGB) at the Whiteshell Laboratories for the Siting Task Force (STF) [17]. Transmissivities were measured in 29 test zones among the three boreholes, using a variety of test methods, where transmissivity is defined as hydraulic conductivity multiplied by the thickness of the water-bearing unit. Their data have been converted to hydraulic conductivity by assuming that the length of the aquifer test zone represents the water-bearing thickness of the unit being tested; where more than one data analysis method was used in a single test zone, the geometric mean for the test zone was calculated. The bedrock hydraulic conductivity listed in Table 4 (5.8×10^{-5} $cm \cdot s^{-1}$) is the geometric mean of values from 15 test locations - Table 5 summarizes the means and ranges of hydraulic conductivities provided by the RH-series boreholes. All of these measurements were performed over depth intervals of 10 m or more, and all intervals include a number of fractures, although in some cases the fractures were apparently filled with secondary minerals. The minimum hydraulic conductivity in Table 5 (8.2×10^{-11} $cm \cdot s^{-1}$) can be considered to represent an upper limit for hydraulic conductivity of the bedrock itself. Groundwater flow is primarily through the fractures.

Table 5: Bedrock Hydraulic Conductivities in the RH-Series Boreholes

Depth Below Rock Surface (m) From	To	Hydraulic Conductivity (cm/s) Geometric Mean	Min	Max	Number of Test Zones
0	100	5.8E-05	5.9E-06	1.8E-03	15
100	200	2.3E-07	8.2E-11	2.0E-04	14

Bedrock porosity consists, in fact, of two components - intergranular or matrix porosity (i.e., the porosity of intact rock) and fracture porosity. Intergranular porosity is a significant property when processes such as matrix diffusion are being considered, and it has been estimated to be between 1×10^{-4} and 1×10^{-3}. Fracture porosity, which controls advective groundwater movement, is normally considered to be 1%.

No dispersivity data are listed for bedrock. Dispersion and diffusion are complex processes in fractured media, and estimates are largely inferential. Bedrock flow is not considered to be a significant transport path for the STDF, meaning that there is no current requirement to attempt to specify and support dispersion parameter values.

Bouldery Sand Till: The cross sections indicate that glacial till is present only in limited areas of the study region. There are no direct measurements of hydraulic properties for this unit in the STDF area, but data have been collected in the Perch Lake Basin by Cherry et al. [18] and Table 4 provides an average for those measurements. The till's poor sorting (wide range of particle size) results in a relatively low hydraulic conductivity - similar to that of shallow bedrock - and a porosity significantly lower than that of the sands that overlie the till. Again, there are no direct measurements of dispersive properties of the till, but it will be argued that the till is not involved in transmitting any significant quantity of groundwater at the STDF site.

Clayey Silt: In the vicinity of the STDF, clayey silts are limited to thin patches overlying the till beneath Lake 233 and to portions of the bedrock valley that extends into Pitcher Plant Swamp. Hydraulic properties listed in Table 4 are taken from similar strata in the Perch Lake basin [19]. The hydraulic conductivity for these very fine-grained materials is the lowest for any of the unconsolidated materials in the study area, and is significantly lower than that assumed for shallow bedrock. Because of this low permeability, lateral groundwater flow through the clayey silts is negligible - there are more permeable units above and below the clayey silt that provide preferential flowpaths. Flow through clayey silt will occur if there are significant differences in hydraulic head above and below the unit (i.e., if the fine-grained material occurs within a region of significant vertical groundwater flow). This situation is known to occur in the southern portion of Duke Swamp [20], but the following section of this report will conclude that there are no regions within the STDF study area with significant vertical flow through clayey silt. The absence of dispersive data for this unit, therefore, is not significant for the current investigation.

Interstratified Sand and Silt: This unit is present almost everywhere in the study area, extending from Lake 233 to the edge of the steep slope leading to Pitcher Plant Swamp (and the gentler slope leading to Duke Swamp) and from the north to the south end of the region covered by

Figure 2. The unit was deposited in water, and lies close to or at the top of the site's sequence of fluvial deposits.

Many samples of this unit have been recovered from boreholes in the vicinity of the STDF footprint. Table 6 summarizes hydraulic conductivities that have been estimated from the grain size information using the Masch & Denny type curves [21]. The materials are listed by soil type (i.e. in terms of their grain size distribution). Samples from the interstratified sand and silt unit certainly fall into the silty very fine sand category in Table 6, but at least some of the fine to very fine sand samples also come from slightly coarser zones in this unit; many of the very fine to fine sands represent a transition zone between the interstratified sand and silt unit and sands. Table 4 recommends that the hydraulic conductivity for silty very fine sand should be applied to the interstratified sand and silt, but the ranges and average values of hydraulic conductivities for the first three soil types in Table 6, are so similar that any or a combination of the units could be applied.

Table 6: Summary of Hydraulic Conductivities Estimated from Grain Size Data for the STDF Site

Soil Type	Hydraulic Conductivity ($cm \cdot s^{-1}$) Mean	Std.Dev.	Min.	Max.	Number of Samples
Silty V.Fine Sand	4.6E-03	2.4E-04	4.4E-03	5.2E-03	9
Fine - V.Fine Sand	4.9E-03	6.9E-04	3.8E-03	5.8E-03	10
V.Fine - Fine Sand	5.8E-03	7.2E-04	3.7E-03	6.7E-03	20
Fine Sand	8.9E-03	9.4E-04	7.4E-03	1.1E-02	19
Medium - Fine Sand	1.1E-02	3.0E-03	1.1E-03	1.6E-02	45
Fine - Medium Sand	1.5E-02	1.8E-03	1.1E-02	1.8E-02	11

Table 4 recommends that a porosity of 0.40 be applied to the interstratified sand and silt unit. This is near the upper end of the range observed for granular sediments, but is appropriate to this case because of the high degree of sorting (limited range of grain sizes) within individual strata contained within the unit. The table also lists longitudinal and transverse dispersivities for the interstratified sand and silt of 5 and 0.5 m, respectively. These values are the midpoint of the range of values employed by Robertson et al. [22] in simulations of the movement of ^{90}Sr from the nearby Nitrate Plant. Although only a portion of the plume track from the Nitrate Plant passes through the interstratified sand and silt unit, we will argue that rates of dispersion in the sands are much lower, which implies that most of the spreading simulated in the modelling studies would occur in the interbedded sand and silt.

Fine-Medium Sand: The dominant unconsolidated material near the STDF site, the sands in this hydrostratigraphic classification, represent both fluvial and aeolian deposits. In the study area, these materials are highly stratified and a number of sub-classifications can be recognized in the unit. Data from the controlled tracer tests conducted just northwest of Twin Lake in the 1980's show that although these sub-classes are frequently present in discrete strata, the zones have

vertical dimensions of a few tens of centimetres and lateral dimensions of a few tens of metres. As a result, although such variations in grain size are frequently observed in cores from a borehole, it is rarely possible to correlate the features from one hole to the next. It can also be argued that variations in the hydraulic properties of such strata are not large enough to warrant efforts to delineate their spatial distribution precisely, particularly at the current level of evaluation of the STDF approach to waste disposal.

The last four soil types in Table 6 are all members of the fine-medium sand hydrostratigraphic unit. Hydraulic conductivities estimated from the grain size information are listed in Table 6. The results show that the ranges of hydraulic conductivities for each soil class overlap, and it is appropriate to consider that the tested samples were drawn from a continuum, rather than a set of discrete groups or classes. The hydraulic conductivity listed for fine-medium sand in Table 4 is higher than the mean value for even the coarsest soil type in Table 6. Hydraulic conductivities were determined for the aquifer to the northwest of Twin Lake using measured hydraulic gradients and flow velocities provided by mapping the movement of non-reactive tracers in a series of experiments conducted in 1982, 1983, 1987 [23][24]. These hydraulic conductivities are based on direct measurements rather than an empirical correlation with grain size distribution, although data from the Twin Lake tracer tests show that estimates from grain size data are within a factor of 2 to 3 for study area sands. The average hydraulic conductivity for fine-medium sand determined in the 1983 tracer experiment [23] was 1.9×10^{-2} cm$\cdot$s^{-1}. This has been recommended as the default value for fine-medium sands in the STDF region.

Sands in this hydrostratigraphic unit, and similar deposits on other portions of the CRL property, are well sorted (narrow range of grain sizes). One should expect that the porosity of this material will be at the upper end of the range generally observed for sands, and is indeed the case. Data from 61 measurements at the Twin Lake tracer test site provided a mean porosity of 0.40, with a normal distribution and a standard deviation of 0.02 [3]. Parsons [25] reported that 153 sands from the Perch Lake area had porosities that ranged from 0.33 to 0.43. For the STDF evaluation, a fine-medium sand porosity of 0.40 is recommended.

Table 4 also lists longitudinal and transverse dispersivities for the fine-medium sand. These data were provided by a 1987 experiment at the Twin Lake tracer test site, and represent "full-aquifer" dispersivities - that is, they include the spreading induced by stratification in the sands, as well as dispersion resulting from intergranular flow within a homogeneous sand stratum. The dispersivities listed in Table 4 are averages of determinations for aquifer transport distances of up to 260 m [24]. Aquifer dispersivities in porous media are often considered to increase as the distance traveled increases, presumably as a result of flow velocity variations in strata of increasing lateral dimensions. This effect was not particularly evident in the data from tests at Twin Lake, and for the present STDF assessment, the measured averages for longitudinal and transverse dispersivities are recommended.

5.2.2 Temporal Fluctuations in Water Table Elevations and Piezometric Heads

The aquifer that underlies the STDF site is recharged by infiltration from Lake 233, by the direct infiltration from rainfall and snowmelt on the sands that cover the region, and in a somewhat convoluted situation, by parts of Twin Lake. The flow system responds to changes in the amount of recharge with rises and falls in the elevation of the water table. Before proceeding with a discussion of the patterns and rates of groundwater flow, this section will discuss information on these fluctuations.

Figure 11 displays measurements of static water elevations made at boreholes TL-1 and TL-8 (see Figure 2 for locations), both of which were installed in 1981 and provide the longest available record of water levels in the area. Both boreholes are equipped with multiple observation wells screened (i.e., open to water movement with the surrounding soil) at various depths. Wells at TL-1 and TL-8 are numbered from the bottom up; for example, TL-1- I is screened at the base of the sand sequence, while TL-1- II is screened near the water table. Such multiple installations allow the determination of the vertical component of groundwater flow.

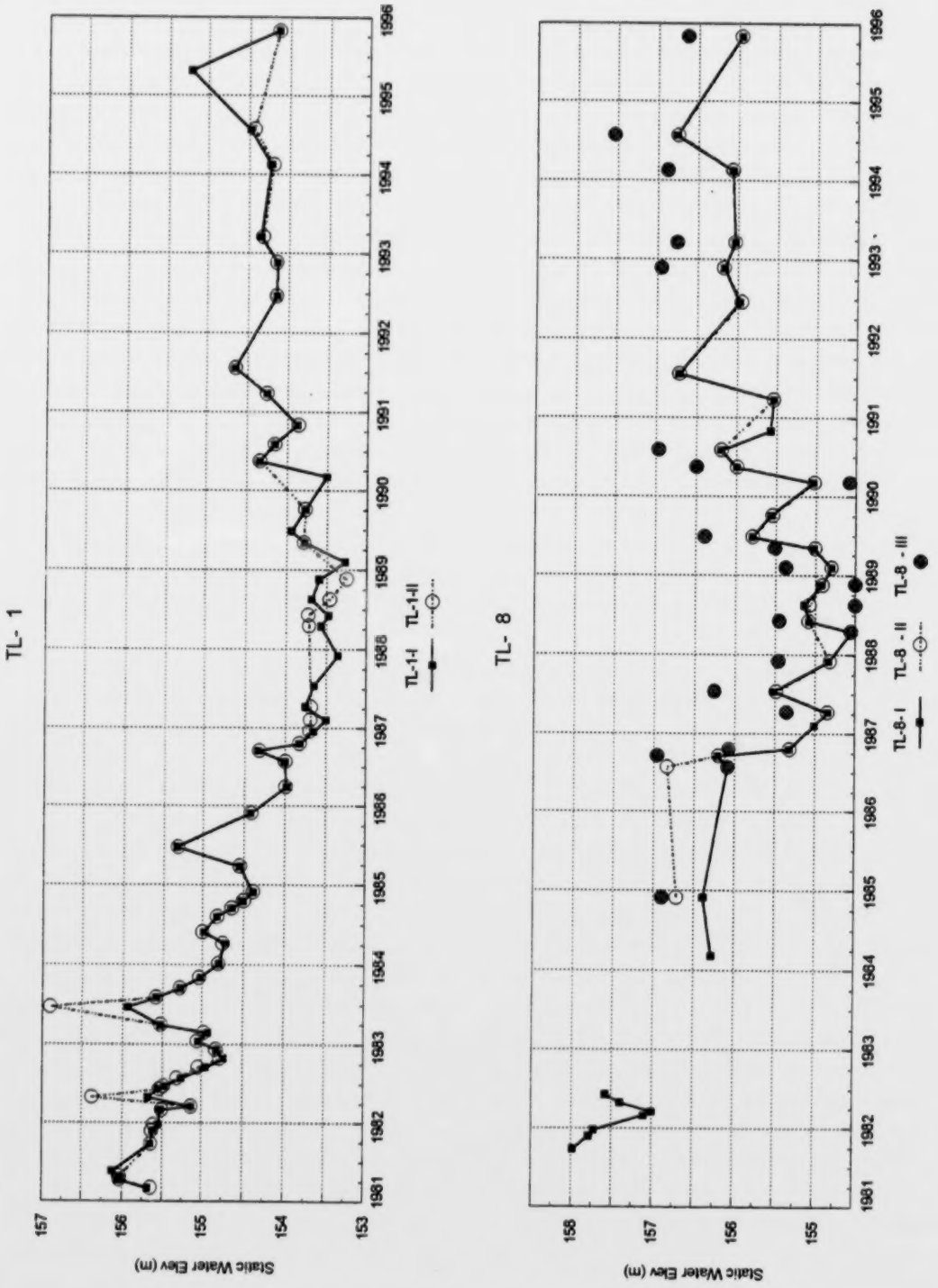

Figure 11. Water table elevation fluctuations between 1981 and 1995 at borehole locations TL-1 and TL-8

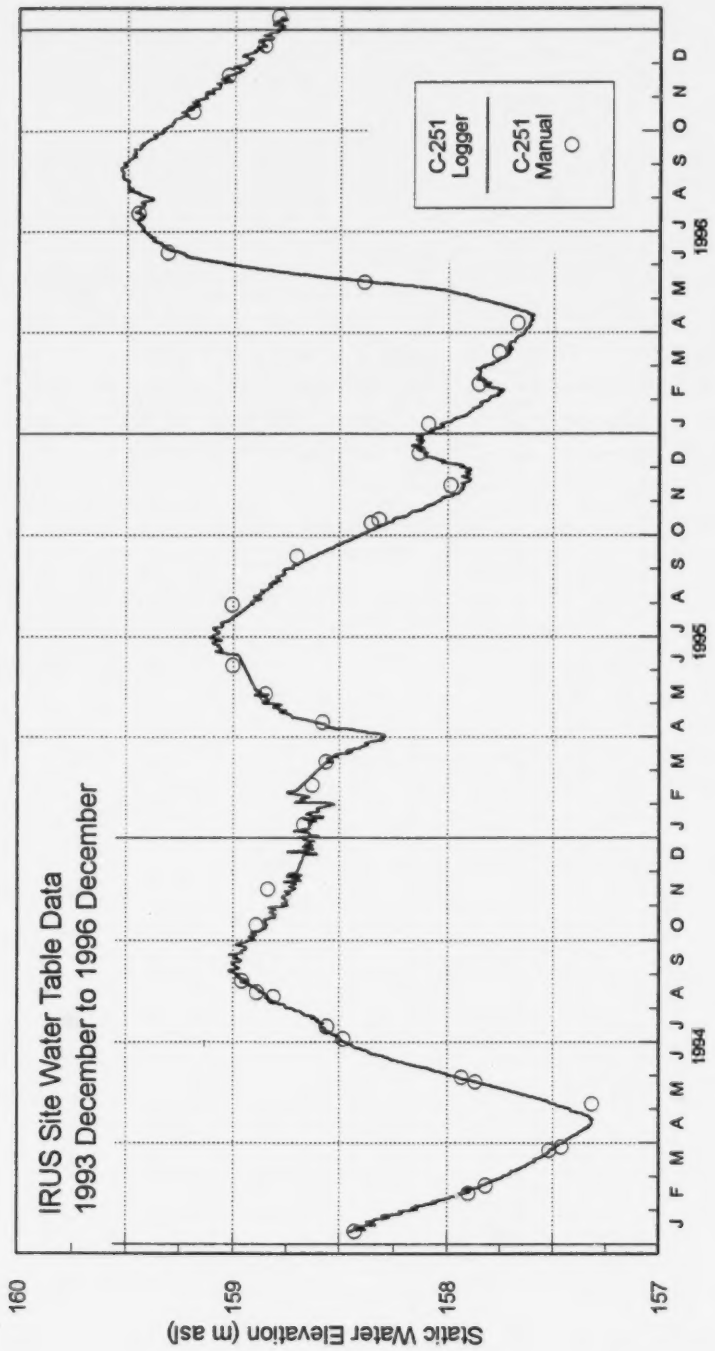
IRUS Site Water Table Data
1993 December to 1996 December
C-251 Logger
C-251 Manual
Static Water Elevation (m asl)
160
159
158
157
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1994
1995
1996

Figure 12. Continuous record of water table elevation fluctuations between 1993 December and 1997 January at borehole location C-251

The frequency of water level measurements has varied over time, ranging from 2 to 8 readings per year. As a result, resolution of the normal annual cycle of water level variations in the Lake 233 aquifer are well-resolved only in some years. High resolution of seasonal changes in water table elevation, however, are available from transducers and a data logger that has collected water elevation measurements at 30-minute intervals at the nearby IRUS site since 1994. Figure 12 shows the record for the water table well in borehole C-251, which has been measured at 30-minute intervals using a pressure transducer and recorded by data logger from 1993 December to the present. The temporal variations in water table elevation recorded at C-251 provide an excellent illustration of the features seen throughout the Lake 233 sand aquifer. The seasonal cycle features a local minimum in water table elevations at the end of March or early April, following the winter when most precipitation is retained at surface in the snowpack. There is a relatively rapid rise to an annual maximum water table elevation in mid- to late summer. The system's response to the spring melt and spring rain accompanied by low rates of transpiration before vegetation is well into the seasonal peak in growth rates. In some years, the summer maximum is followed by slow decline extending through to the following spring, but in years with wet, mild, late autumns (and possibly a relatively early halt in photosynthetic activity), some water is again available to recharge the aquifer in early winter. In 1994/95, the late season infiltration was sufficient to halt the water table decline in December and January, while in 1995 November and December there was a 30 cm increase in water table elevations.

Continuous head measurements at C-251 and periodic measurements of other wells throughout the Lake 233 aquifer show very similar patterns of water level elevation changes. It is evident from all of the data sets that have a sufficient duration and scope that these annual variations are superimposed on longer term trends in water table fluctuation. These variations are linked to changes in precipitation and the timing of precipitation and snowmelt events. Wilkinson [26] provides a detailed analysis of the probability of occurrence of various maximum water table elevations at the nearby IRUS site, and although the temporal response, may be slightly different than that for the STDF region, it is undoubtedly similar. Wilkinson concluded that the 100-year return period maximum water table would be 1 m higher than the observed maximum at the IRUS site, which occurred in 1981 June. For the STDF reference design [27], the maximum water table was assumed to be 1 m higher than the 1995 March water table contours.

Across the study area, changes in water table elevation are similar in their timing, although the magnitude of variations is normally greatest in recharge areas and smallest near groundwater discharge zones (where surface water levels are the primary control on groundwater elevations). Nevertheless, fluctuations are not entirely uniform, and flowpaths do vary somewhat over time, particularly where the water table is relatively flat. Flowpath variations will be discussed in the following section. It is worth noting that water table fluctuations are closely reflected by changes in hydraulic head in deeper portions of the groundwater flow system - that is, vertical hydraulic gradients do not show substantial temporal variations.

5.2.3 Groundwater Flow Paths

Figure 13 to Figure 16 show water table contours for four sets of measurements collected in 1987 July, 1990 August, 1992 June, and 1995 March. These dates represent some of the more complete data sets, but also provide some representation of points on the seasonal cycle, with March frequently near the annual minimum, June the rising limb of the spring recharge event, July the maximum, and August the start of the water table recession. There has been no evidence for any significant horizontal anisotropy in the hydraulic conductivity of local sands (Section 5.2.1), so it is reasonable to assume that groundwater flow lines will be orthogonal to the water table contours.

Based on an assumption of no horizontal anisotropy, the four water table maps show the area where water in the aquifer has passed beneath the STDF footprint. In three of the four cases, the widest portion of the STDF's groundwater track is along the downgradient edge of the site's footprint. Flowlines converge on the Pitcher Plant Swamp, in response to the steepening of hydraulic gradients as the discharge area is approached and by the thickening of the aquifer over the path between the STDF and the groundwater discharge area. The track provided by the 1990 August data set is at substantial variance with the other three data sets, and show a secondary broadening of the track near Pitcher Plant Swamp. Much of this broadening stems from kinks in the water table contours for elevations of 149 and 150 m, and this may be at least in part a contouring artifact. It seems clear that the bedrock valley that extends to the eastern end of Pitcher Plant Swamp provides a channel for groundwater convergence, and this should minimize the spreading of any contaminant plume emanating from the STDF footprint.

The groundwater flow system in the overburden around the STDF site is unconfined - that is, there are no layers or strata with very low permeability to isolate the sand aquifer from surface waters. The plan views of the groundwater flowpaths associated with the STDF on Figure 13 through Figure 16 show that in all four cases, the track of any contaminant plume from the facility passes beneath Twin Lake. The question that this configuration immediately raises is whether a leachate release from the STDF would discharge into Twin Lake and adversely affect surface water quality. To gain some appreciation of the vertical components of flow in the overburden, Figure 17 and Figure 18 display hydraulic heads along cross sections B-B' (west-east from Pitcher Plant Swamp to Lake 233), and D-D' which runs north-south along the west side of Twin Lake and terminates in Duke Swamp.

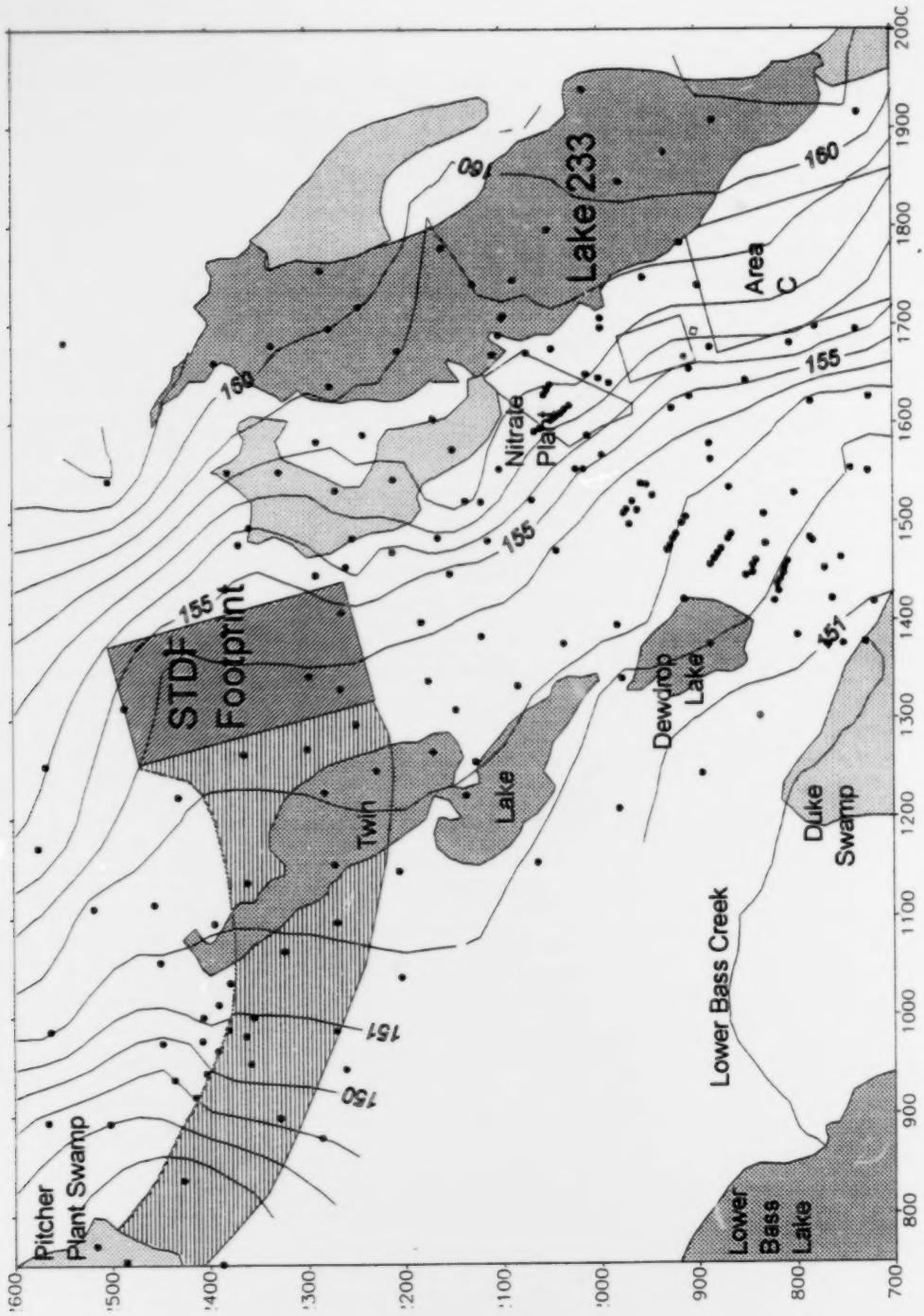

Figure 13. Contours of the elevation of the water table in the region containing the STDF reference site in 1987 July.

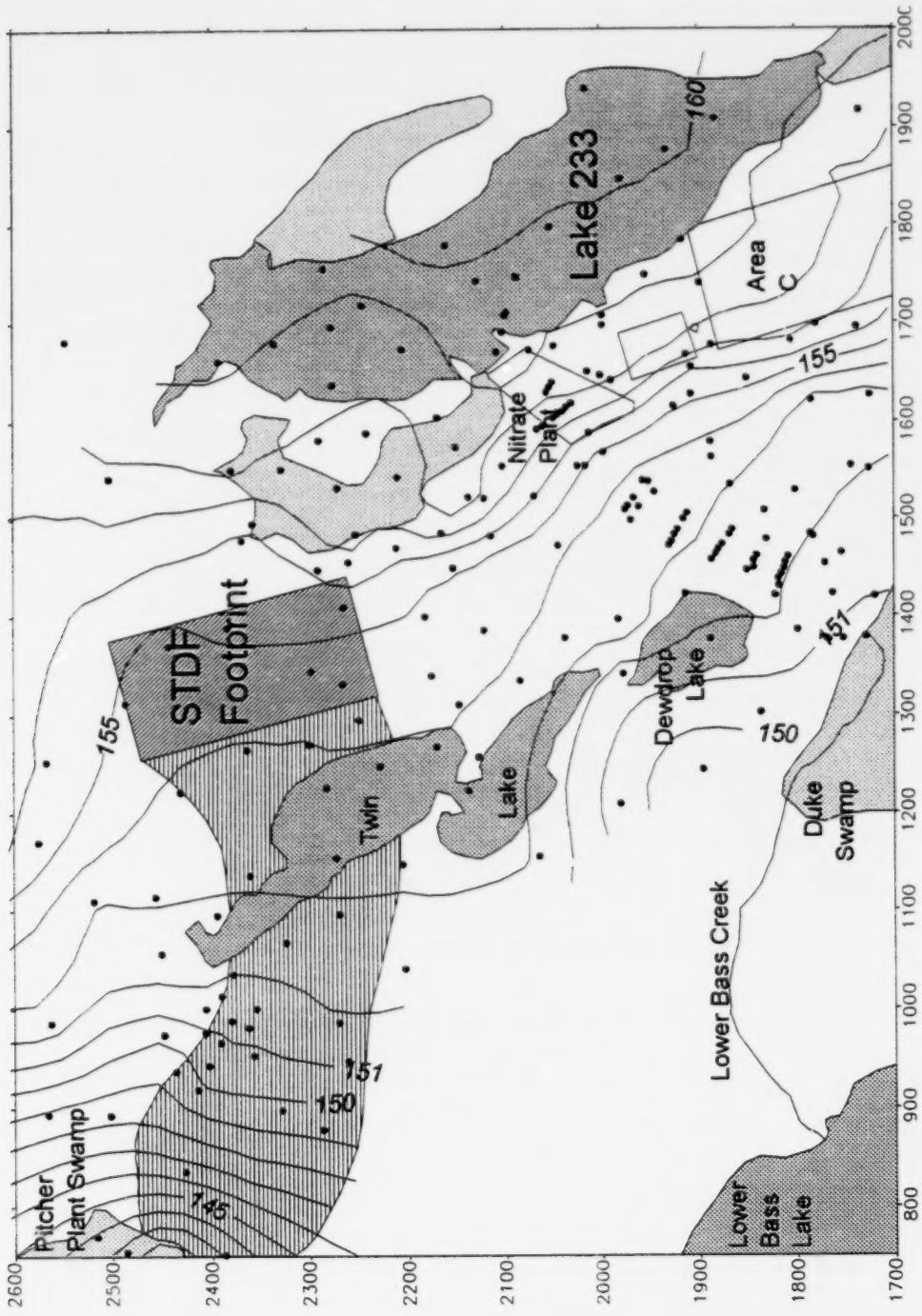

Figure 14. Contours of the elevation of the water table in the region containing the STDF reference site in 1990 August.

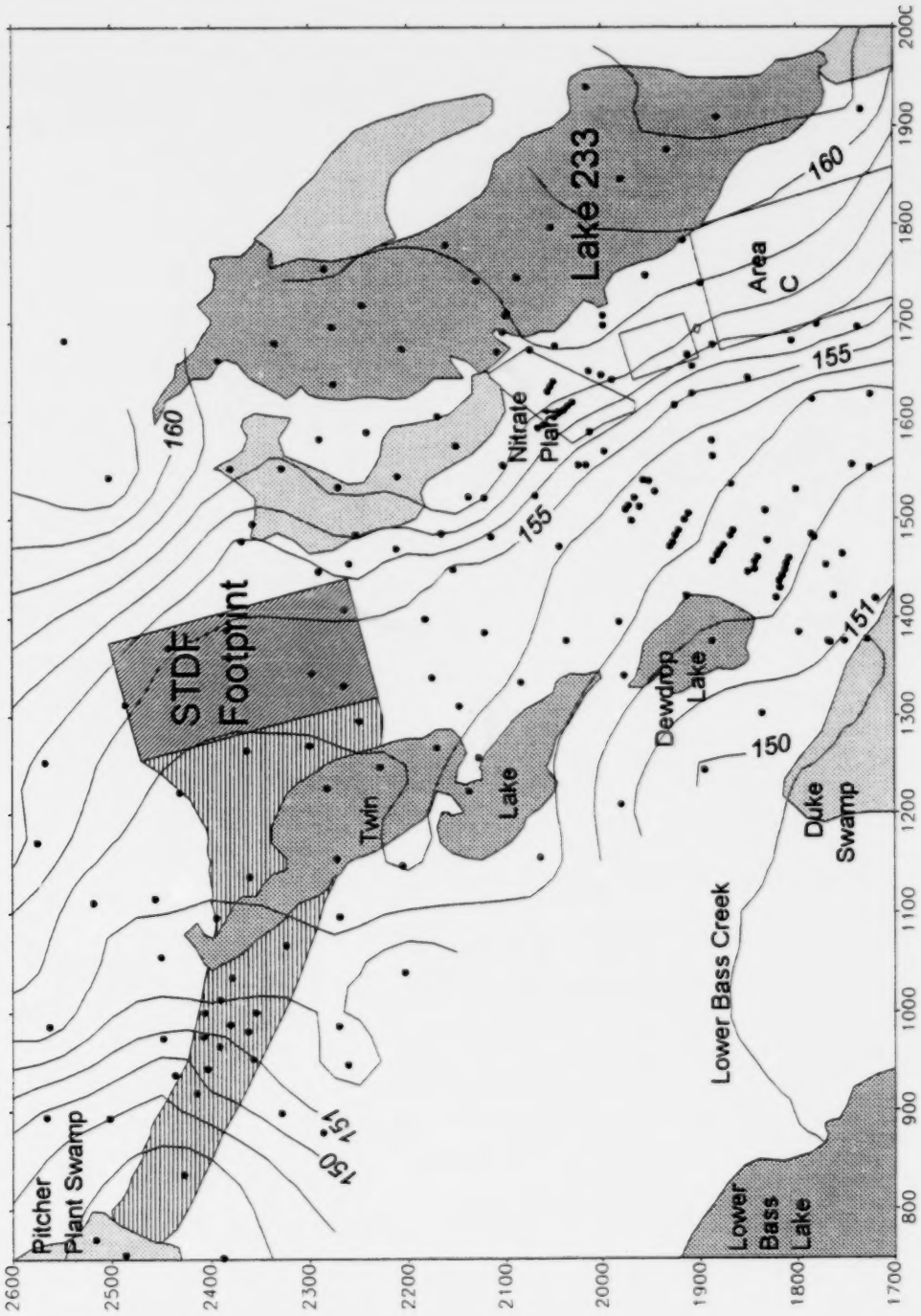

Figure 15. Contours of the elevation of the water table in the region containing the STDF reference site in 1992 June.

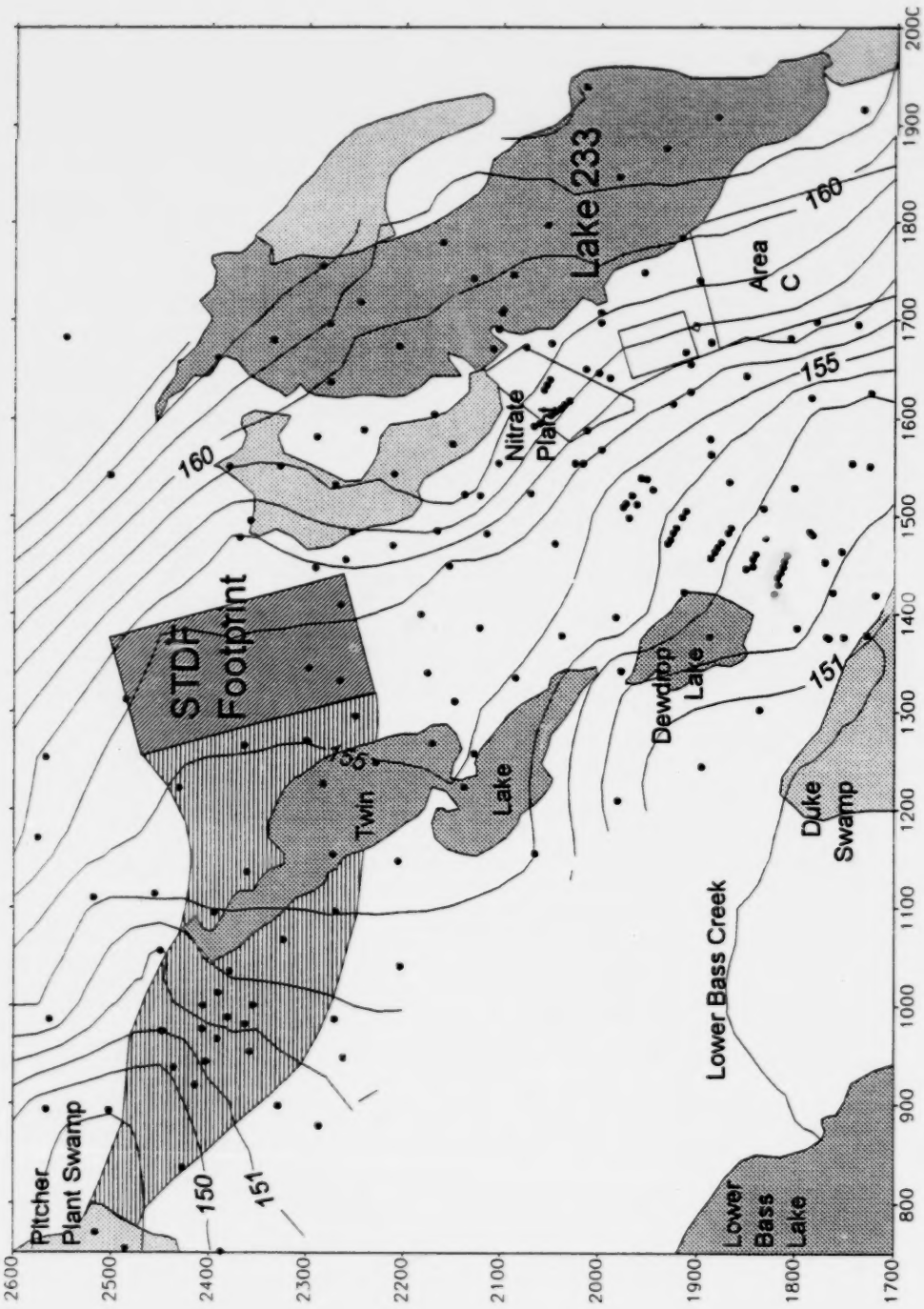

Figure 16. Contours of the elevation of the water table in the region containing the STDF reference site in 1995 March.

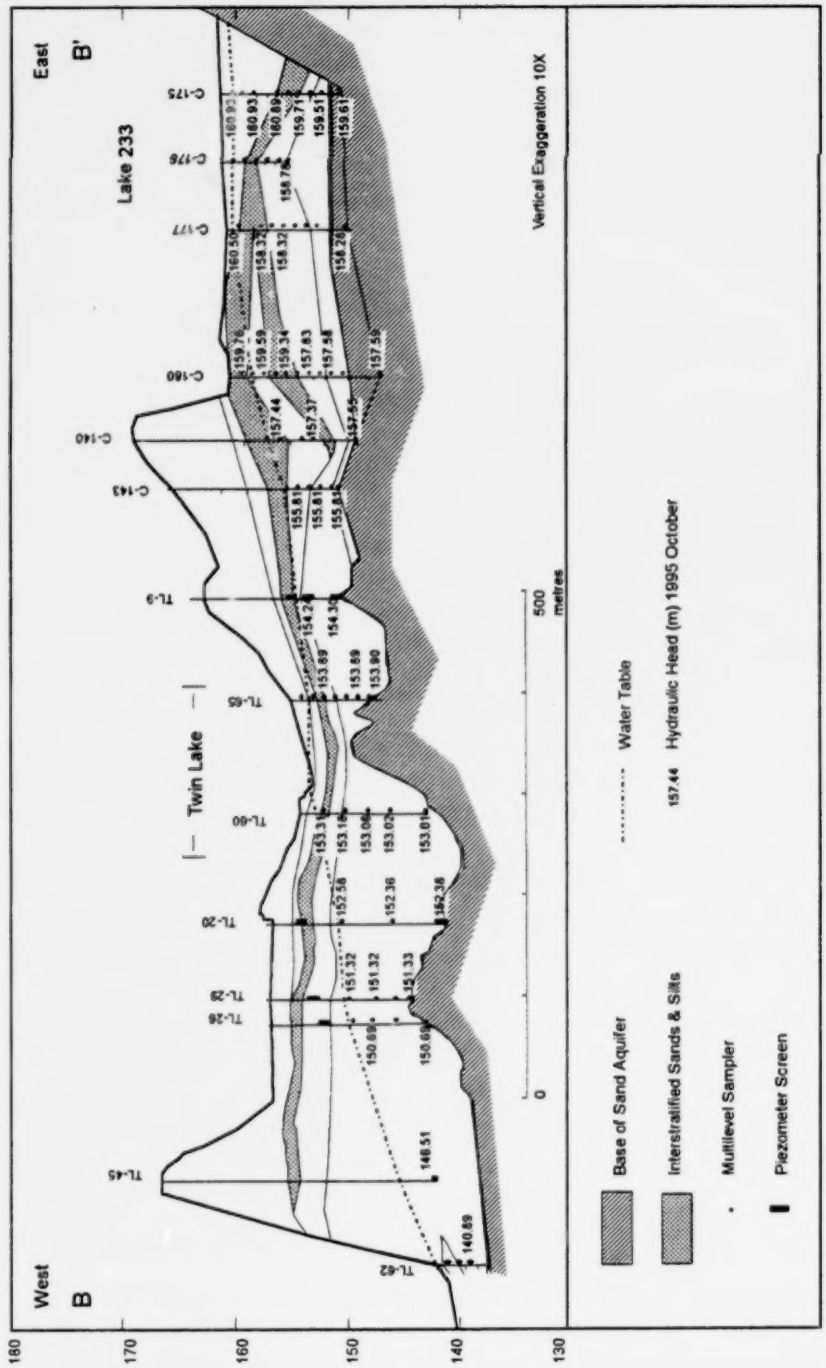

Figure 17. Vertical distribution of hydraulic head along cross section B-B'.

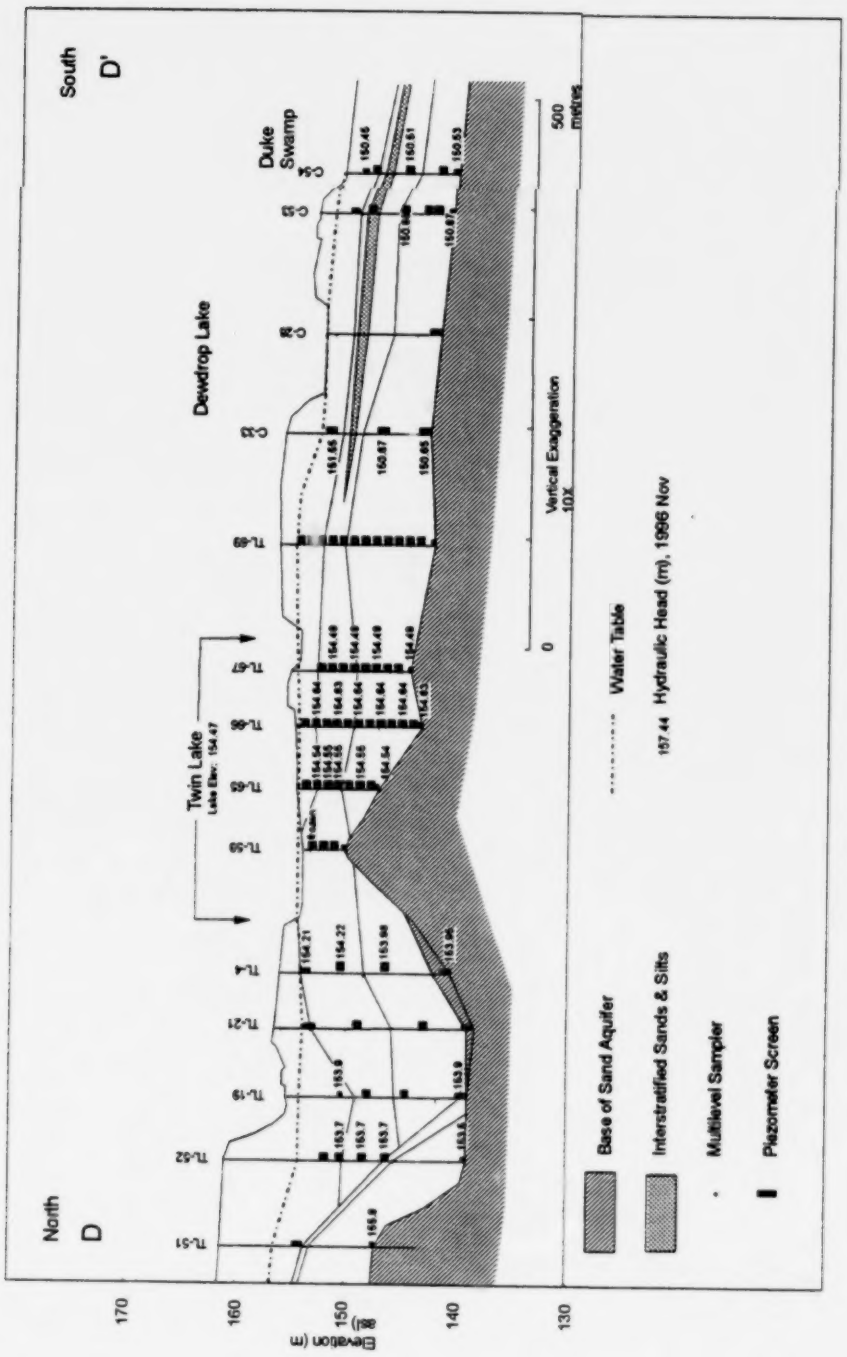

Figure 18. Vertical distribution of hydraulic head along cross section D-D'.

Section B-B' (Figure 17) is oriented approximately parallel to the lateral component of groundwater flow. Hydraulic head distributions beneath Lake 233 show strong downward gradients - static water levels in piezometers screened in the sands below the interstratified sand

and silt (ISS) unit are a couple of metres lower than water levels in the lake and in piezometers above the ISS unit. The distribution of hydraulic head shows that water is moving into the ground from Lake 233, but that the ISS is a significant impediment to flow. Once water reaches the underlying sands, movement is lateral and to the west. Hydraulic head differences between wells screened at various depths in boreholes C-140, C-143, and TL-9 are identical to within a few centimetres, and show that there is almost no vertical component to groundwater movement in this region, which is just south of the STDF footprint. Vertical gradients are also absent from the portion of the flow system penetrated by holes TL-20, 29, and 26. There are strong upward gradients in Pitcher Plant Swamp (as evidenced by the springs at the margin of the wetland and by the artesian discharge from the well at the base of the sand at nearby TL-64) although vertical gradient data are not available for TL-62.

The area of key interest, however, is the region around Twin Lake. The hydraulic heads shown on Figure 17 at GL-60 are clearly indicative of recharge from Twin Lake into the sand aquifer on the western (i.e., downgradient) side of the lake. What is not so evident is discharge from the aquifer into Twin Lake on its eastern (upgradient) side. Borehole TL-65 is located near the eastern shoreline of the lake (and essentially on the shoreline at times of high lake level). The hydraulic head data plotted for the various wells at TL-65 on Figure 17, show almost no vertical gradient - the static water elevation recorded for the deepest piezometer at TL-65 is only 1 cm higher than the elevation of water in the shallowest of the measured piezometers. Although this indicates upward flow, the difference in static level in the wells is not significant; the measurements are frequently only reliable to 2 to 3 cm. Despite this, surface evidence at times of low water level in Twin Lake, clearly show that groundwater is discharging into the lake along a section of the eastern shore extending from the base of the small peninsula that separates the Lake's two basins to some point that appears to be between TL-65 and TL-59 (Figure 9). The presence of groundwater in Twin Lake is confirmed by the presence of slightly elevated levels of chloride in the lake that are attributed to the discharge of groundwaters that have been recharged from Lake 233, which receives road salt runoff from the CRL highway.

Another view of the hydraulic head distribution near Twin Lake is provided by Figure 18, in a cross section that is oriented at approximate right angles to groundwater flow - for this figure, lateral groundwater flow is out of the plane of the cross section. Most of the hydraulic head data shown on Figure 18 were measured in 1996 November. At that time, the lake was frozen but the elevation of the ice surface was 154.47 m above sea level (m asl). Observation wells at TL-59, which in 1997 November were in Twin Lake, were also frozen. Wells at TL-65, 66, and 67 showed almost constant hydraulic heads with depth in the sand aquifer - that is, there was almost no vertical gradient evident within the aquifer. Heads in TL-65 and 66 were, however, significantly higher than the water level in Twin Lake. The head distribution shows that there is indeed a gradient to drive discharge into Twin Lake; but also suggests that the major impediment to vertical groundwater flow in the vicinity of Twin Lake is the lakebed itself. Other features on Figure 18 are the downward hydraulic gradients at TL-4, located on the eastern side of the northern arm of Twin Lake (Figure 9), the downward hydraulic gradients south of Twin Lake at C-33, and the upward gradient at C-54, by the edge of Duke Swamp.

To summarize the discussion of groundwater flow around Twin Lake, it is evident from hydraulic head data that water routinely flows from Twin Lake into the ground at the lake's north and south ends, except at times of very low water levels, when both ends of Twin Lake dry up. When

boreholes TL-59 and TL-60 were installed in 1987 August, for example, the entire portion of Twin Lake to the north of these holes was dry. It is also evident from hydraulic head measurements in wells and from visual observations of seepage that the section of the eastern shoreline of Twin Lake just north of the dividing peninsula is an area of groundwater discharge. The slightly elevated concentrations of chloride in Twin Lake are attributed to the presence of groundwater that originated in Lake 233. The key factor responsible for the convoluted hydrology around Twin Lake is the bedrock ridge that trends almost north-south beneath the central section of the lake. The bedrock high is actually exposed as outcrop on the southwest shore of the lake, but even though the rock ridge is buried beneath overburden under the central section of the lake, it still represents a major constriction in the thickness of sand available for groundwater flow. This constriction, in turn, results in upward hydraulic gradients, and overland flow in Twin Lake becomes the path of least resistance for some of the groundwater. The bedrock surface falls steeply from the ridge that bisects Twin Lake, and the resultant rapid thickening of the aquifer beneath the north and south ends of the lake makes flow through the sands the easiest route available for water movement in these regions.

What is certain is that Twin Lake is more than a depression that happens to intersect the water table and that it has an active circulation, with groundwater entering the east-central section of the lake and lake water entering the sand aquifer at the northern and southern ends of the lake. Any groundwater that enters Twin Lake through the east-central discharge area will either evaporate or will re-enter the ground in systems that drain to both Pitcher Plant Swamp and Duke Swamp. It is also certain that groundwaters passing beneath the north end of the STDF footprint also pass beneath, rather than through, Twin Lake.

What remains uncertain are the precise boundaries of these discharge and recharge regions in Twin Lake. It is, therefore, also uncertain whether the current footprint for the STDF is positioned far enough to the north that all leachate released by the site would pass under, rather than through, Twin Lake. For the current STDF assessment, the decision that has been made is to assume that the site's footprint either now is, or will be, positioned far enough to the north that any leachate releases will remain in the subsurface until the aquifer terminates in Pitcher Plant Swamp. If the STDF site is to be pursued, resolution of these uncertainties and a clear determination of the appropriate location for the facility will be required.

Using the assumption that the STDF footprint is not positioned over a section of aquifer that discharges into Twin Lake, the dimensions of an aquifer plume arising from the STDF are listed in Table 7. The minimum and maximum plume widths are drawn from the plots displayed on Figure 13 through Figure 16. Because of the convergence of groundwater flow on the Pitcher Plant Swamp discharge area, in most of the cases the widest part of the plume was immediately

downgradient of the STDF footprint, although the plume displayed on

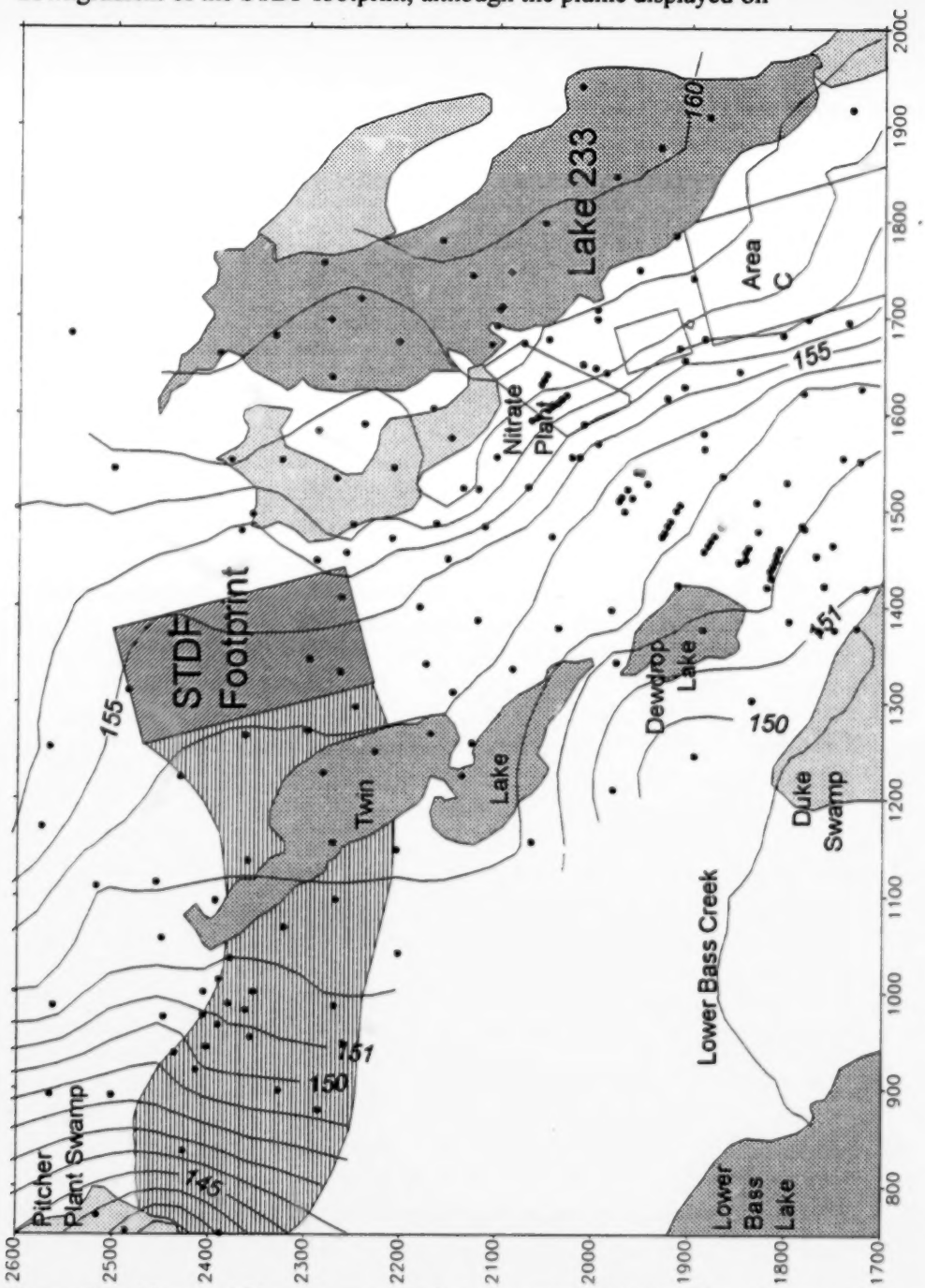

Figure 14 widens to 250 m between Twin Lake and the Pitcher Plant Swamp. Because this broadening is considered anomalous in the context of the groundwater flow system, a most probable plume width that approximately matches the length of the STDF (a nominal 200 m) has been recommended for the study at hand.

Table 7: Recommended Dimensions of an Aquifer Contaminant Plume Arising from the STDF

	Minimum	Maximum	Most Probable
Recommended STDF Plume Width (m):	50	250	200
Recommended STDF Plume Thickness (m):	3	7	4.5
Recommended STDF Plume Length (m):	570	700	600

The maximum thickness of any contaminant plume generated by the STDF is limited by the saturated thickness of the aquifer, which ranges up to about 7 m beneath and downgradient of the footprint. There are two approaches to an estimation of the minimum thickness of aquifer that a contaminant plume from the STDF could occupy. One is to consider the quantity of water added to the aquifer during its passage beneath the STDF footprint, and assume that contaminant inputs occur uniformly from the footprint area. Using current rates of infiltration, and assuming no significant vertical dispersion, one calculates a leachate plume thickness of 0.45 to 0.65 m at the downgradient margin of the site's footprint. If a cover that reduces infiltration through the wastes were installed, the plume thickness calculated by this procedure would be reduced. Over a time scales of years, however, the minimum plume thickness will be controlled by the variability in water table positions over time. For the period of record (Figure 11), this is almost 3 m. The most probable plume thickness (4.5 m) is derived from the contaminant plume that has developed downgradient of the former Nitrate Decomposition Plant site located just south of the STDF footprint.

Minimum and maximum plume lengths represent the downgradient distances from the western and eastern boundaries of the STDF to the Pitcher Plant Swamp groundwater discharge area. The recommended distance of 600 m was selected to reflect the fact that leachate flux increases with downgradient (i.e. westerly) distance as groundwater passes beneath the STDF footprint, assuming that infiltration through the STDF is uniform.

5.2.4 Groundwater Flow Velocities and Residence Times

Hydraulic gradients (the changes in water table or piezometric elevation over given horizontal distances) in the aquifer beneath and downgradient of the STDF footprint were determined using seven sets of water table elevation data, including those shown on Figure 13 to Figure 16; Table 8 lists the distances between measurement points. Borehole TL-47 is located near the upgradient (eastern) margin of the STDF footprint, and TL-54 is 125 m west near the site's downgradient margin. The remaining boreholes listed on Table 8 are located close to the mid-line of the portion of aquifer that would be affected by any release from the STDF, and the cumulative distance between TL-54 and TL-64 (570 m) represents a minimum flowpath length. For the calculations listed below, hydraulic gradients determined from the seven data sets were averaged - with the exception of the gradients observed between TL-21 and TL-13, the standard deviation of

the observed gradients was less than 20%. Between TL-21 and TL-13 the standard deviation of the observed gradients was 44%, a result of transient infiltration from Twin Lake.

Table 8: Groundwater Flow Velocities and Residence Times from the STDF Footprint to Pitcher Plant Swamp. (The terms "grain size" and "tracer" in the column headings refer to the source of the hydraulic conductivity used in the velocity and residence time calculations.)

Observation Well	Distance (m)	Average Hydraulic Gradient	Avg Linear Velocity (m/d) Fine Sand Grain Size	Fine-Med Sand Grain Size	Tracer	Residence Time (days) Fine Sand Grain Size	Fine-Med Sand Grain Size	Tracer
TL-47								
TL-54	125	0.010	0.19	0.27	0.40	667	469	313
TL-21	173	0.006	0.12	0.17	0.25	1450	1019	680
TL-13	62	0.011	0.21	0.30	0.45	292	205	137
TL-28	121	0.019	0.36	0.52	0.78	334	234	156
TL-57	92	0.015	0.30	0.42	0.63	310	218	145
TL-64	124	0.050	0.96	1.37	2.06	128	90	60
Min Flowpath Length:	572 m		Tot. Groundwater Residence Time (Years):			6.9	4.8	3.2

Note: Residence times are calculated from the downgradient boundary of the STDF.

Groundwater flow velocities were calculated for segments of the flowpath between each borehole using the average hydraulic gradient for that segment, the average porosity (0.40), and three values of hydraulic conductivity. The first is the mean hydraulic conductivity for fine sands estimated from grain size distribution data, while the second is the average of grain size data estimates of hydraulic conductivities for the medium-fine and fine-medium sands. These hydraulic conductivities are listed in Table 6. The third hydraulic conductivity used in the flow velocity and residence time estimates is the weighted average hydraulic conductivity for fine-medium sands provided by the Twin Lake tracer test data (1.9×10^{-2} cm·sec^{-1}). This is the highest mean hydraulic conductivity determined for the study area and is the default value recommended for fine-medium sands in Section 5.2.1, on an assumption that shorter subsurface residence times would be conservative in terms of downstream impacts from the STDF. Considering flow in the fine-medium sands, therefore, produces average linear groundwater velocities of between 0.25 m·d^{-1} (from the downgradient boundary of the STDF footprint to Twin Lake) and 2.1 m·d^{-1} (where steep gradients occupy the section of aquifer immediately upgradient of Pitcher Plant Swamp). The minimum groundwater residence time from the downgradient edge of the STDF footprint to the groundwater discharge area is 3.2 years. Flowpaths that involve lateral movement through fine sands could produce residence times that are approximately twice as long as the minimum figure.

5.2.5 Effects of a Domestic Water Supply Well on Aquifer Flow Fields

There are no current users of groundwater in the study area. One scenario to be considered in assessing the impact of the STDF on possible local populations is the case of a household

installing a domestic water supply well. The annual volume of water drawn from a domestic well was estimated in the IRUS preliminary safety assessment [3] to be 390 $m^3 \cdot a^{-1}$, and the same value has been considered to be appropriate to scenarios involving the STDF. Pumping a well will induce changes in the aquifer flow field, and the question arising is whether such pumping could significantly affect groundwater flow patterns. A simple water balance calculation has shown that such a well would have a radius of influence of less than 20 m.

6. 3-D GROUNDWATER FLOW MODEL OF THE REFERENCE SITE

6.1 Conceptual and Mathematical Model of Flow

A 3-dimensional groundwater flow model has been used to simulate the flow regime in the region surrounding the STDF site and used to calculate both flowpaths for groundwater that passes beneath the STDF footprint and travel times to the location(s) of discharge to surface. It should be emphasized at the outset that the flow modelling performed is of a scoping nature only, and that the work presented here is derived from a previous, more regional, modelling project that simulated overburden flow in the entire Lake 233 - Twin Lake region.

The mathematical model describing flow within porous medium is based on the principle of conservation of mass and Darcy's Law and is written in the form of a three dimensional (3-D) continuity equation [28]. The equation is derived with regard to the unknown function, the hydraulic head. The groundwater flow velocity is then calculated on the basis of the simulated head and Darcy's Law.

The 3-D groundwater flow equation is solved numerically to calculate the hydraulic head distribution within the model domain. The numerical solution is based on the finite difference code as described by MacDonald and Harbaugh [29] and is implemented in the USGS code MODFLOW. Three-dimensional groundwater flowlines from the proposed STDF facility to discharge zones are calculated using the post-processing package MODPATH, documented in Pollock [30]. In MODPATH, the 3-D velocity field is calculated from the simulated hydraulic head distribution and a particle tracking routine is used to determine flowlines.

The first step in modelling is to develop a conceptual model of the aquifer which involves the interpretation of the flow-controlling features. In order of the following discussion, these are

- system boundaries, and the conditions that exist at those boundaries, and
- the spatial distribution of hydraulic properties in the region of interest as defined by an interpretation of stratigraphy and lithology.

6.2 Simulation Limits and Properties

6.2.1 Model Domain and Boundary Conditions

The model domain chosen for flow modelling is the Lake 233/Twin Lake drainage basin shown in Figure 19. The base of the model domain is a no-flow boundary defined by the base of the

surficial sands, which in most cases corresponds to the bedrock surface but, in some areas, is the surface of glacial till or basal clayey silt strata. For the simulations, the base of the sands in the southern portion of the model domain was defined by borehole data augmented with ground penetrating radar (GPR) information. The base of the sands in the northern portion of the domain (including Twin Lake), however, was inferred only from GPR data collected on a 100 m grid, and did not incorporate borehole information. As a result, there are some differences between the shape of the base of the model domain and the topography of the base of the sands shown on Figure 4 through Figure 8 and the bedrock topography displayed on Figure 9. The most notable difference is the essential absence of the east-northeast trending bedrock ridge beneath Twin Lake that is discussed in Section 4.2 of this report.

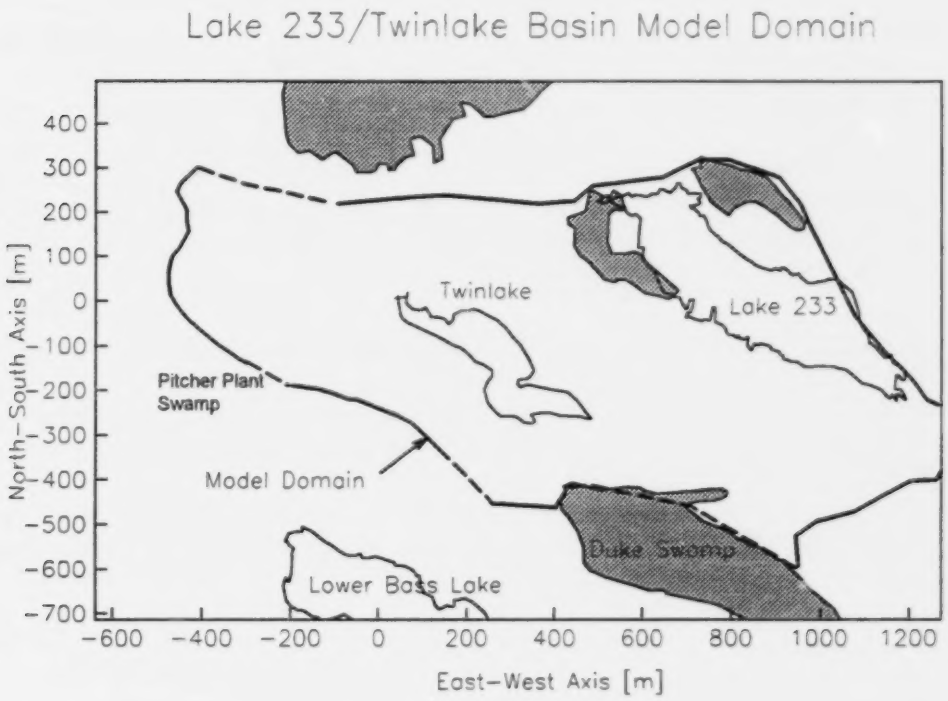

Figure 19. Plan view of the Lake 233/Twin Lake basin model domain. Solid line represent no flow boundaries; dashed lines represent specified head boundaries.

The eastern boundary of the model domain is the bedrock ridge that lies east of Lake 233 [11], and this is taken to be a no-flow boundary. No-flow boundaries are also applied to the northern and southern edges of the model domain, which are oriented parallel to groundwater flow lines defined by field observations. Specified (constant) head boundaries are applied along the southwest and western boundaries of the domain to the margins of the topographic lows of Duke Swamp and Pitcher Plant Swamp, with no-flow segments applied where bedrock outcrops have been mapped. Figure 19 shows the lateral boundary conditions applied for modelling; sections of

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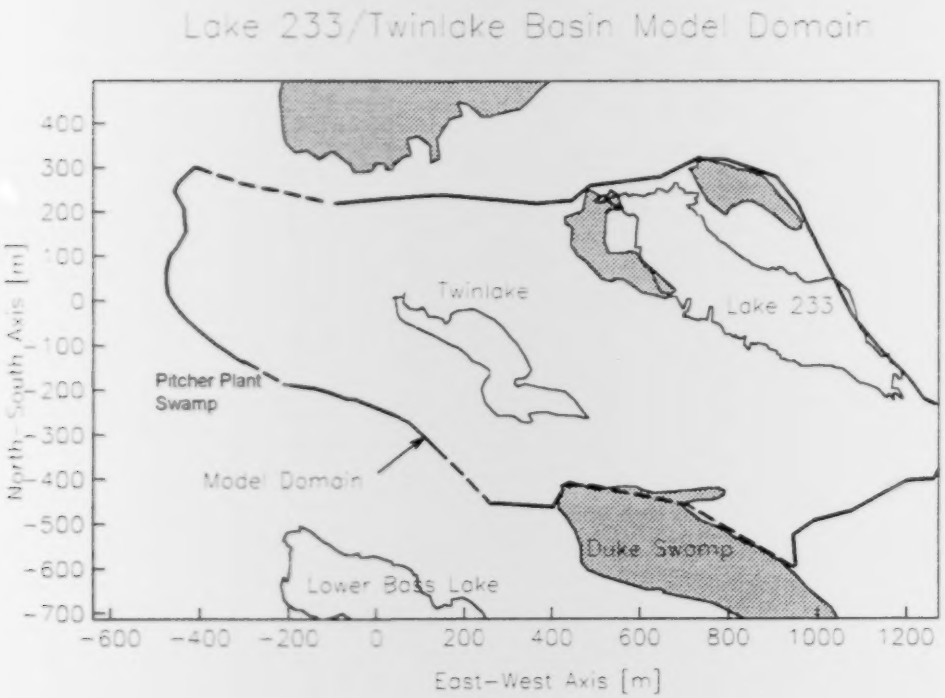

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the model domain boundary marked with solid lines represent no flow boundaries, while portions of the perimeter having dashed lines represent constant head boundaries.

For the model domain's upper surface, a constant head boundary is applied at Lake 233 and Twin Lake (with elevations fixed at 161.5 and 155.1 m, respectively [25]). At all other locations the upper surface is treated as a specified flux boundary and a recharge rate of 0.3 m/a, estimated from field studies reported in [4], is applied.

6.2.2 Aquifer Stratigraphy and Hydraulic Conductivity for Flow Modelling

Overburden in the study area is composed predominantly of medium and fine-grained sands (classified on the Wentworth scale), with some interstratified sands and silts. Cross sections showing aquifer stratigraphy are provided in Section 4.2, and hydraulic properties of the stratigraphic units are also summarized there. It should be noted, however, that the modelling reported here is a subset of a prior study and there are some minor differences in aquifer properties used in the numerical simulations and those listed in Section 4.2.

Variability in the hydraulic conductivity of the medium and fine sands is generally less than 30% and for flow modelling the sands were treated as a single, homogeneous, unit. The lower-permeability interstratified sands and silts, however, represent a significant control on the flow system and are incorporated into the model.

Horizontal grid discretisation is 10 m in the longitudinal and transverse directions. Vertically, the grid is discretized into five layers. The horizontal hydraulic conductivity of the sands was assigned a value 1.35×10^{-2} cm·s^{-1} based on hydraulic conductivities provided by flow modelling of the Nitrate Plant plume site, approximately 300 m from the STDF footprint [31]. A vertical anisotropy of 3 (i.e., horizontal hydraulic is three times greater than vertical hydraulic conductivity) is assigned throughout the model domain except at Lake 233 and Twin Lake. At these locations, the low permeability zones beneath the lakes was accounted for by assigning a vertical anisotropy of 10 to the top layer of the model mesh.

6.3 3-D Numerical Simulations of the Groundwater Flow System

3-D numerical simulations of the flow system were performed for the given boundary conditions and aquifer parameters. Figure 20 shows the simulated equipotentials along the top layer of the domain, representing the water table elevation. Total recharge into the domain through constant head boundaries specified at lake beds and from recharge is approximately 5,500 m^3·d^{-1}.

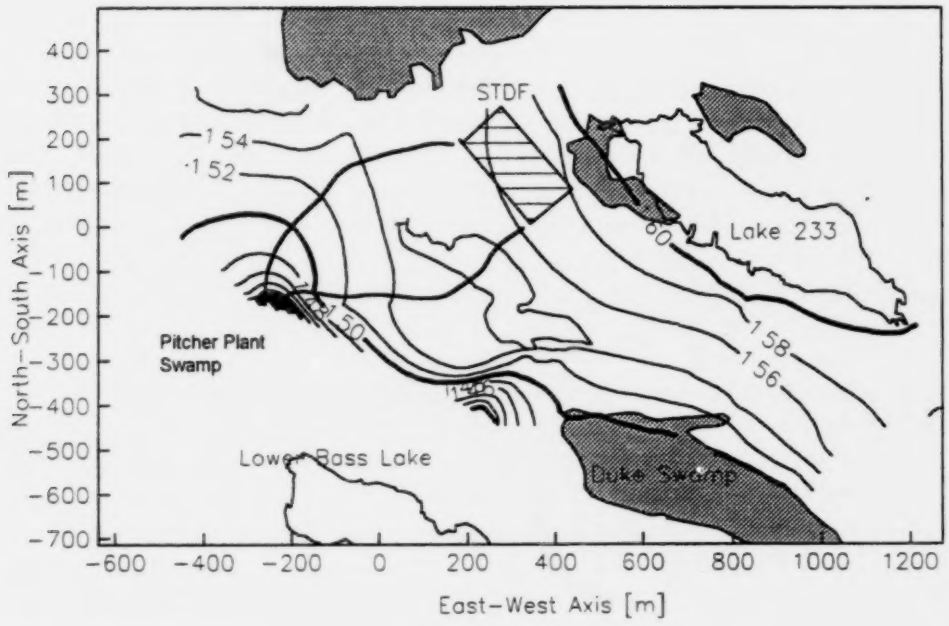

Figure 20. Simulated water table elevations and pathline trajectories from the STDF footprint.

One means of evaluating the accuracy of the flow simulation (and the conceptual model of the aquifer that underlies the simulation), is through a comparison of simulated and measured hydraulic heads. Simulated heads were compared against measured heads at selected TL-series wells from July 1987. Table 9 lists the TL-series well locations where comparisons were made and the simulated and measured heads. The comparison of simulated and measured hydraulic heads yielded a mean difference of 2.6 m, a factor of four greater than the mean difference between simulated and measured heads for the simulations of the flow system at the nearby Nitrate Decomposition Plant site [31]. The larger differences for the basin scale flow simulation performed here is attributed to the simplified aquifer stratigraphy and bedrock topography that were employed in this simulation.

Better agreement between simulated and measured heads could almost certainly be achieved by adjusting model parameters and boundaries to improve the fit between the conceptualized flow system and the aquifer as defined by site-specific information.

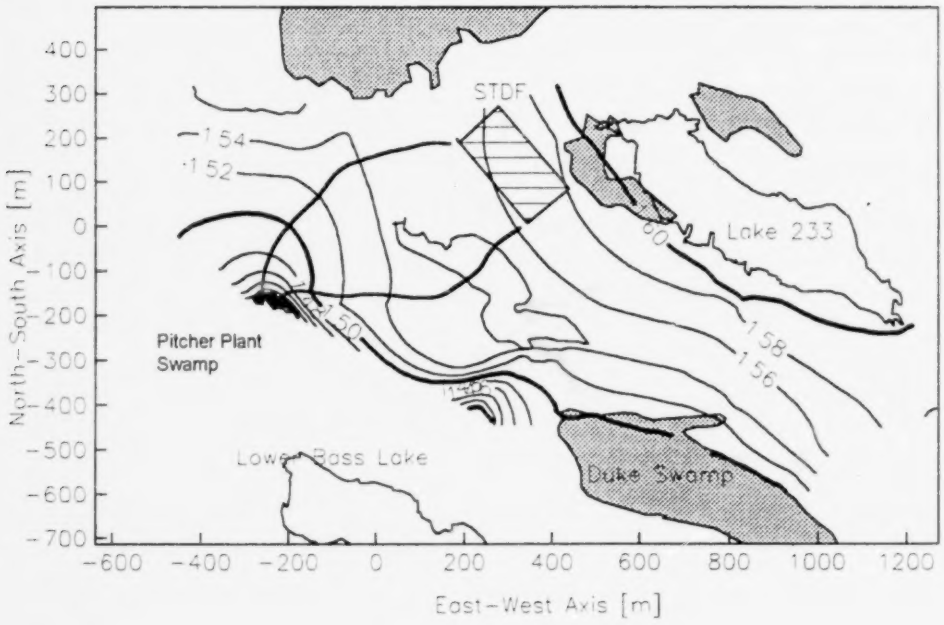

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Table 9: Simulated and Observed Hydraulic Heads at Selected TL-Series Wells

Well ID	Simulated Head	Observed Head	Sim - Obs.
TL-19	154.6	152.4	2.2
TL-20	155.1	151.8	3.3
TL-22	153.0	150.5	2.5
TL-29	152.6	151.0	1.7
TL-41	158.8	156.4	2.4
TL-44	158.2	154.7	3.5
TL-54	155.8	153.2	2.6
TL-58	154.3	152.0	2.3

Pathline trajectories have been calculated to define the travel path from the STDF to the discharge zone. Pathline trajectories of particles originating on the western edge of the STDF Vault footprint are shown in Figure 20. The discharge zone is the Pitcher Plant Swamp to the west-northwest of Twin Lake. A porosity of 0.4 (Section 4.2) was applied to calculate linear groundwater velocities. Table 10 lists the starting location of the pathline trajectories, travel distance, travel time and average velocity over the travel path. Travel time from STDF to the discharge zone is of the order of 10 years and average velocity along the pathline trajectories approximately 0.15 m/d. These linear velocities are within a factor of two of linear velocities measured along the flowpath from Lake 233 to Duke Swamp [32].

Table 10: Numerical Model Pathlength, Travel Time and Average Velocity for Pathline Trajectories from the STDF to the Discharge Zone

Particle Origin	Pathlength (m)	Travel Time (years)	Avg. Velocity ($m \cdot d^{-1}$)
Southwest Corner	645	10.8	0.16
Northwest Corner	640	11.6	0.15

6.4 Discussion

The numerical model's predicted flowpath for a plume emanating from the STDF footprint is similar to those determined from the field observations, reflecting the fact that the shape of the modelled water table is similar to that provided by the field data sets. The model, however, predicts an average water table elevation that is approximately 2.5 m higher than that which is observed. This discrepancy shows that some components or parameters in the conceptual model that the simulation represents, are not accurate reflections of the real flow system. Inverse modelling, however, provides no unique solutions and hence, no unambiguous indications of where inaccuracies lie. Increases in the model's hydraulic conductivities would be one avenue to a closer match between observed and simulated water table elevations. The value of hydraulic conductivity applied to fine-medium sands in the model is only 17% smaller than that used in the direct calculation, and adjustment to it is only unlikely to bring the simulated water table into

accord with observations. The numerical model, however, also includes a layer assigned a low vertical hydraulic conductivity (representing the interstratified sand and silt unit) and increasing this hydraulic conductivity would also lower the simulated water table.

The other area of apparent conflict between the simulation and calculations based on observed data are the groundwater velocities and groundwater residence times. In this case, both data sets are calculated results, rather than direct observations in the field. The Twin Lake tracer experiments provided direct flow velocity information for half of the STDF flowpath, and the 1987 experiment that used tritiated water showed that groundwater residence time in the fine-medium sands, between a point about 50 m west of Twin Lake and Pitcher Plant Swamp, was 270 days. Flow velocities in the portion of aquifer between the STDF footprint and the Twin Lake tracer test site would be expected to be lower, since hydraulic gradients are lower near the STDF. It is, however, very unlikely that flow velocities near the STDF would be as low as 5 to 10 $cm \cdot d^{-1}$, which would be required for the total residence time to match that predicted by the numerical simulation. The velocities and residence times given in Section 5 (yielding an average velocity over the entire flowpath of 46 $m \cdot a^{-1}$), have been applied in the performance assessment.

7. AQUIFER CHEMISTRY

7.1 Introduction

Groundwater major ion chemistry in the vicinity and downgradient of the STDF has been determined in the past as part of two general programs. The first has been a broad survey of groundwater quality in the Lake 233 - Twin Lake area, undertaken in association with site characterization work for the IRUS site assessment and for the delineation of flow and aquifer chemistry related to the Nitrate Plant plume studies. The second program that has supported the collection of aquifer chemistry data has been studies relating to controlled tracer injection and transport studies performed downgradient of the northwest corner of Twin Lake, most recently in 1990.

7.2 Regional Water Chemistry

One of the key features of some of the groundwaters is the presence of chloride ion at concentrations above what would be considered normal background for this region - about 1 $mg \cdot L^{-1}$. This is attributed to water that has recharged from Lake 233, which receives runoff from the CRL plant highway. The chloride, therefore, can be used as a marker for Lake 233 recharge, and the data on water chemistry has been classified according to Cl^- concentration. Table 11 provides a summary of average concentrations for major ions using three categories: chloride concentrations below 2 $mg \cdot L^{-1}$ (representing direct recharge through the sands downgradient of Lake 233; chloride concentrations greater than 10 $mg \cdot L^{-1}$ (recharge from Lake 233); and a transitional category between these two. For most of the flow system, this classification also translates to a vertical sequence, with the (relatively) high chloride concentrations occurring in the lower portion of the aquifer, the low Cl^- water near the water table, and the transitional group in between. Note that the recorded temperatures are

measurements taken at the wellhead in the flow cell used for pH and redox measurements; as a result, the average temperatures listed on the table should be taken as an upper limit that in many cases was subject to slight warming while the samples were being collected.

Table 11: Major Ion Groundwater Chemistry in the Lake 233 - Twin Lake Region

Parameter	Units	Choride Concentration Ranges (0 - 2 ppm) Mean	(2 - 10 ppm) Mean	(> 10 ppm) Mean
pH		5.93	6.20	5.79
Lab pH		6.08	6.41	6.18
Eh	(mV)	287	204	125
Temp.	(C)	15.6	13.4	15.0
DO	(ppm)	4.0	3.7	1.3
Cond.	(uS)	85	89	97
HCO3	(mg/L)	47.5	49.3	41.8
Cl	(mg/L)	1.30	4.95	12.5
SO4	(mg/L)	6.42	9.19	6.71
NO3	(mg/L)	0.89	0.77	1.42
F	(mg/L)	0.58	0.77	0.70
Ca	(mg/L)	11.4	14.1	12.7
Mg	(mg/L)	4.44	3.91	3.88
Na	(mg/L)	3.01	4.93	6.02
K	(mg/L)	5.76	2.32	1.86
NH4	(mg/L)	1.70	0.88	0.16
Fe	(mg/L)	1.04	2.50	1.73
Mn	(mg/L)	0.13	0.19	0.10
SiO2 tot.	(mg/L)	14.3	18.0	17.23
TDS	(mg/L)	98	112	107

Despite the minor effects of road salt, all of the overburden groundwaters in the area of interest have a similar chemistry. The waters are slightly acidic, with average pHs of near 6, and low in total dissolved solids (TDS), which range, on average, from 100 to 130 $mg \cdot L^{-1}$. The waters can be broadly characterized as calcium bicarbonate, with sodium being the next most abundant cation in many of the samples. Waters tend to become more reducing with depth (and with residence time in the flow system); this is reflected by the decreases in both redox potential measured with a platinum electrode and in the concentration of dissolved oxygen. These trends are generally more evident when data from a single nest of piezometers are considered, but they are apparent even in the averaged data set given in Table 11.

One of the most significant consequences of this trend towards more reducing conditions is the mobilization of iron and manganese. Iron, in particular, is frequently present at concentrations greater than those recommended (on an aesthetic basis) for drinking water (0.3 $mg \cdot L^{-1}$). In individual samples, iron and manganese concentrations of up to 40 and 0.65 $mg \cdot L^{-1}$, respectively, have been measured, and the abundance of ferrous iron in the groundwaters is readily evident in

the discharge area at the eastern edge of Pitcher Plant Swamp, where oxidation upon exposure to air has resulted in the formation of large deposits of iron oxyhydroxides.

Although iron is less abundant than calcium and sodium in many samples, its redox-sensitive character, and the habit of iron oxyhydroxides to act as readily-available solids which can either co-precipitate or sorb many other cationic elements, makes it a notable species in the system. All of the samples for which there were sufficient data to perform WATEQF calculations are under equilibrium conditions, saturated with respect to a series of iron oxyhydroxides as well as with respect to amorphous quartz. The absence of calcite saturation is worthy of note - this reflects the very low concentrations of carbonate minerals in the study area overburden and can also be used to support comments that the discharge of groundwater from bedrock to overburden is a minor phenomenon, at the most, in the study area.

Table 12 is a summary of a separate set of groundwater chemistry data collected from the axis of the Twin Lake Tracer Test Site flowpath in the fall of 1990, as part of the baseline data for a controlled injection experiment conducted at that time. Samples were collected at 1 m depth increments at 5 locations over a 40 m distance. The results show that the aquifer in this area can be considered to contain two masses of water - infiltration unaffected by road salt in Lake 233, which occupies the upper two metres of the zone of saturation, and a deeper body of water with chloride concentrations averaging just under 6 $mg^{\cdot}L^{-1}$. As with the data from the wider set of wells presented in Table 11, there is a trend to lower dissolved oxygen, lower redox potentials, and higher iron concentrations with increasing depth in the aquifer, but, on average, both shallow and deep waters at the Tracer Test Site exceed the drinking water objective for iron.

Table 13 lists information on major ions and standard water quality parameters, as well as concentration data for a suite of trace elements, from groundwaters collected upgradient of various existing waste management facilities in the same dune ridge aquifer system as the STDF site. The closest of the three wells sampled is only 300 m from the STDF footprint, and there is no reason to expect that background water quality for trace elements is significantly different in the portion of the aquifer overlain by the STDF.

Table 12: Major Ion Groundwater Chemistry at the Twin Lake Tracer Test Site

Parameter	Units	Water Table (0-2 m) Samples Mean	Deep-Aquifer Groundwaters Mean
Field pH		5.59	5.80
Lab pH		5.78	5.93
Eh	(mV)	72	-43
Temp.	(C)	8	8
DO	(ppm)	1.9	1.3
Cond.	(uS)	36	45
HCO3	(mg/L)	14.4	20.1
Cl	(mg/L)	0.84	5.73
SO4	(mg/L)	6.02	7.74
NO3	(mg/L)	0.97	1.06
F	(mg/L)	0.05	0.03
Ca	(mg/L)	3.48	5.21
Mg	(mg/L)	1.31	1.64
Na	(mg/L)	1.43	2.89
K	(mg/L)	0.90	1.03
Fe	(mg/L)	0.78	1.54
Mn	(mg/L)	0.01	0.03
SiO2 tot.	(mg/L)	7.8	13.4
Al	(mg/L)	0.07	0.06

Table 13: Major Ion and Trace Element Concentrations from Wells Upgradient of the ACS Pits (Well C-205), the Nitrate Plant (Well C-3-I), and Area C (Well C-263)

Element	All Concentrations in mg/L C-205	C-3-I	C-263
Field pH		6.41	6.83
Field Eh		230	140
Temp		6.6	6.6
Conductance	104	292	437
Diss. O2		0.01	0.005
Alk. as HCO3	18.8	93.1	85.2
Dissolved Carbon			
Inorganic		12.4	5.6
Organic		2.7	2.3
SO4	6	9.9	2.7
Cl	7.4	28.5	92.4
NO3		<0.05	1.2
F	0.4	0.3	0.4
PO4		<0.2	<0.2
Ca	5.70	19.2	12.2
Mg	2.90	7.0	3.8
Na	4.70	10.2	46.0
K	1.6	1.4	2.4
Fe	0.01	15.9	44.0
Mn	0.05		
Si			
Al		<0.06	<0.06
Sr		0.087	0.093
Be	< 0.0003		
Li		<0.005	<0.005
Ag	< 0.014		
Ba	0.023		
Zn	0.010	<0.012	<0.012
Cu	< 0.009	<0.005	<0.005
Ni	0.009	<0.009	<0.009
Pb	< 0.040	<0.09	<0.09
Co	< 0.006	<0.012	<0.012
Cr	0.009	<0.007	<0.007
Cd	< 0.003	<0.015	<0.015
Mo	< 0.009		
V	< 0.009	<0.016	<0.016
As	< 0.012	<0.15	<0.15
Se	< 0.060		
Sb	0.024		
Hg	< 0.024		9.5E-05

7.3 Aquifer Mineralogy

Sands are the dominant material in the aquifer beneath and downgradient of the STDF. The sands' mineral composition is essentially that of a granite, with plagioclase (calcium-sodium) feldspars, quartz, potassium feldspars, and muscovite/sericite making up 90% or more of the particles. Hornblende, biotite, magnetite, and garnet comprise most of the remainder. As noted in the previous section, carbonate minerals are almost absent from the sands. Solid organic carbon makes up between 0.02 and 0.04% by weight of the sands at the Twin Lake Tracer Test Site, which lies along the STDF flowpath.

Although the sands' mineralogy is that of a granite, studies of radionuclide behaviour in other contaminant plumes at CRL has indicated that secondary minerals coating the particles play the predominant role in sorption for some radionuclides. Hydrous iron oxides (both amorphous and at least partially crystalline) appear to be the dominant reactive secondary mineral phase.

8. SUMMARY AND RECOMMENDATIONS

The location selected for the assessment of the Sand Trench Disposal Facility (STDF) concept is a ridge of dune sand in the CRL Outer Area (Figure 1). It is approximately 600 m north-northwest of Waste Management Area C, where low-level solid wastes are currently being stored and which is located in the same dune (Figure 2). The location chosen was selected from a review of potential sites for future waste disposal facilities conducted by Inch et al. [2]. That review was constrained to the portion of the Perch Lake basin that lies within AECL property and to the portion of the Maskinonge Lake basin that lies on AECL property to the northeast of Maskinonge Lake. The terms of reference for that review sought information on sites where unsaturated zone thicknesses exceeded 5 m over an area of at least 0.75 ha, and preference was given to sites where subsurface flowpaths of at least 200 m could be anticipated. The region hosting the STDF footprint was identified in that survey as the largest single block on CRL property where the criteria above could likely be met.

This report provides a description of the morphology of the study area and comments on current vegetation, agricultural and forest potential (both very limited), and site climate. For the hydrogeologic assessment of the site, precipitation and evapotranspiration are the key climatic parameters - CRL site data for the past 30 years provide an annual average total precipitation of 831 mm, and an average evapotranspiration rate (for the forested conditions that currently exist on the site) of 530 mm. The STDF footprint covers an area where unsaturated zone thicknesses range from near 5 to in excess of 12 m, using the 1995 March water table elevations and current topography. A unit of interstratified sand and silt lies beneath the dune ridge; beneath the sand and silt unit there are more sands (of fluvial origin), patchy, apparently thin, deposits of till (sometimes overlain with a thin basal clayey silt), and an irregular bedrock surface.

The sands are high permeability materials, and the STDF footprint overlies an active, unconfined, groundwater flow system that carries water from Lake 233 (located about 250 m east of the STDF site), and infiltration that enters the aquifer directly through the surficial sands, to groundwater discharge areas in a series of wetlands that drain to Maskinonge Lake. The STDF

overlies the portion of the aquifer that discharges to Pitcher Plant Swamp. The aquifer sands are stratified, and tracer tests conducted in the 1980's in a portion of the STDF flowpath have shown that the sands form strata with thicknesses of several tens of centimetres and lateral dimensions of several tens of metres. Hydraulic conductivities within these strata are very uniform, but there are appreciable variations between strata. Hydraulic conductivities that have been measured or estimated (from grain size distribution data) for various sub-units of the aquifer sands provide average values ranging from 8.9×10^{-3} mc's^{-1} (fine sands) to 1.9×10^{-2} cm's^{-1} (medium sands), a two-fold variation.

At this stage of the site evaluation, detailed determination of the role of the lower-permeability interstratified sands and silts in controlling groundwater flow was not considered. Some portion of the STDF flowpath will be in these materials, however, and the field data provide horizontal hydraulic conductivities in the interstratified sand and silt unit are two to five times lower than those of the sands. Hydraulic conductivities of the clayey silts, till, and crystalline bedrock, are at least 50-fold and in many cases several orders of magnitude lower than those of the sands. This, and the absence of any indications of significant hydraulic connection between the sands and underlying materials (from field observations of hydraulic head), have lead to an assumption that the base of the sands is the effective base of the flow system that could be affected by the STDF.

Flowpaths for groundwater passing beneath the STDF footprint were graphically determined using water table elevation contour maps of four sets of measured hydraulic heads. Table 7 summarizes dimensional data for the zone in the aquifer that could be affected by releases from the STDF, and Figure 13 to Figure 16 show the water tables and the potential contaminant plume flowpaths. Table 8 summarizes groundwater velocities and residence times between the downgradient (western) margin of the STDF footprint and Pitcher Plant Swamp using mean hydraulic conductivities for fine and fine-medium sands. The minimum subsurface residence time, 3.2 years, was determined using information provided by observations of flow velocity at the Twin Lake tracer test site.

Section 6 of this report summarizes methods, input information, and results of a three-dimensional numerical simulation of groundwater flow in the region surrounding the STDF. The modelling is a subset of a larger-scale simulation of groundwater flow and transport in the Lake 233 region conducted by Klukas and Moltyaner [31]. A key point of difference between the numerical simulation and the information discussed in Sections 4 and 5 is the configuration of the bedrock surface - the model employed a surface constructed from ground penetrating radar (GPR) information in the northern half of the area of interest here, while the information presented and discussed in Sections 4 and 5 uses a bedrock surface defined by a combination of GPR and borehole data. The mesh used in the numerical modelling does not include a buried bedrock ridge beneath Twin Lake depicted on the map of bedrock topography (Figure 9), and only partly reflects the bedrock valley that falls from the northwest corner of Twin Lake to the groundwater discharge area at the eastern margin of Pitcher Plant Swamp. The numerical simulation produced a water table that exceeds the observed water table by approximately 2.5 m, and provides a groundwater residence time of about 10 years for flow from the STDF footprint to Pitcher Plant Swamp. The residence time recommended in Section 5 of the report (3.2 years) is partly based on direct observations of groundwater flow made during the Twin Lake tracer tests, and is believed to reasonably represent flow in the fine-medium sands of the aquifer. It takes no account for the time required for water movement through the interstratified sands and silts that underlie the

STDF footprint and is therefore, a probable underestimate of the true water residence time in the subsurface. Nevertheless, from experimental information gathered along the STDF flowpath, and from the behaviour of contaminant plumes from other waste management facilities in the same aquifer system, an aquifer residence time of about three years continues to be considered as a reasonable estimate.

Section 7 of the report provides a summary of groundwater chemistry in the vicinity of the STDF site. Groundwaters in the area are dilute and near neutral in their pH. Lake 233 receives some runoff from the CRL plant highway, and as a result also receives some road salt contamination - chloride concentrations of up to 100 $mg \cdot L^{-1}$ have been observed near the south end of the lake and the point of entry of road drainage. Lake 233 is frequently not well-mixed, and chloride concentrations measured in groundwater recharged from Lake 233 in the vicinity of the STDF are less than 25 $mg \cdot L^{-1}$. Shallow groundwaters are oxidizing, and are dominated by bicarbonate, calcium, and sodium. Deeper groundwaters, and in particular waters that have been recharged from Lake 233, are reducing, and the absence of oxygen has allowed for the dissolution of iron from the aquifer sediments. Iron concentrations in deep overburden groundwaters range up to 11 $mg \cdot L^{-1}$, making it a major component of some waters' dissolved salt load. This pattern is again one that is widespread in overburden aquifers at CRL, and should not be considered to be a feature peculiar to the STDF site.

One recommendation arising from this review and compilation of the setting and hydrogeology of the region being considered in the STDF scoping study is that details of the relationship between Twin Lake and the local overburden aquifer should be defined before a comprehensive assessment is made. From the data presently available, it is known that any mobile contaminants escaping into the ground from the northern portion of the current STDF footprint would pass beneath Twin Lake en route to Pitcher Plant Swamp. The point where groundwaters could enter Twin Lake is considered to probably be south of the current footprint, but the actual location remains uncertain. Flowpaths from the STDF footprint that lead to discharge into Twin Lake are considered undesirable, partly because they would allow for only very limited subsurface attenuation before any contaminants could come to surface, and partly because waters in Twin Lake recharge the sand aquifer on flowpaths that lead both to Pitcher Plant Swamp and to Duke Swamp. This would increase the area that could potentially be affected by an STDF, and the complexity of environmental impact assessments.

A second recommendation, linked in part to the first, is that a conceptual model that more closely represents local geologic and boundary features be developed and implemented in a numerical code. One objective of such a modelling study would be to assist in the definition of interactions between the sand aquifer and Twin Lake. Another would be to re-assess groundwater flow velocities (and review flowpaths) after a simulation that provides a better match between modelled and observed hydraulic heads can be achieved.

It is clear that interactions between the aquifer around the STDF footprint and Twin Lake are likely to be a focus of discussion in any review of the potential for establishing a low level solid waste disposal facility. There is no *a priori* reason why the STDF has to be positioned in this particular location, and other parts of the CRL site could also be considered.

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